NASA TECHNICAL
MEMORANDUM

NASA TM X-64706

ASSESSMENT OF AND STANDARDIZATION FOR
QUANTITATIVE NONDESTRUCTIVE TESTING

By Robert W. Neuschaefer and James B. Beal
Quality and Reliability Assurance Laboratory

September 30, 1972

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

1. REPORT NO. NASA TM X -64706	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE ASSESSMENT OF AND STANDARDIZATION FOR QUANTITATIVE NONDESTRUCTIVE TESTING		5. REPORT DATE September 30, 1972
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Robert W. Neuschaefer and James B. Beal		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS Applied Technology Branch Analytical Operations Division Quality and Reliability Laboratory*		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D. C. 20546		13. TYPE OF REPORT & PERIOD COVERED NASA Technical Memorandum
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

*George C. Marshall Space Flight Center
 Marshall Space Flight Center, Alabama 35812

16. ABSTRACT

This document assesses present capabilities and limitations of Nondestructive Testing (NDT) as applied to aerospace structures during design, development, production, and operational phases. It will help determine what useful structural quantitative and qualitative data may be provided from raw materials to vehicle refurbishment.

This assessment considers metal alloy systems and bonded composites presently applied in active NASA programs or strong contenders for future use.

Quantitative and qualitative data has been summarized from recent literature, and in-house information, and presented herein along with a description of those structures or standards where the information was obtained. Examples, in tabular form, of NDT technique capabilities and limitations have been provided. NDT techniques discussed and assessed were radiography, ultrasonics, penetrants, thermal, acoustic, and electromagnetic. Quantitative data is sparse; therefore, obtaining statistically reliable flaw detection data must be strongly emphasized.

The new requirements for reusable space vehicles have resulted in highly efficient design concepts operating in severe environments. This increases the need for quantitative NDT evaluation of selected structural components, the end item structure, and during refurbishment operations.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
	Unclassified - unlimited James B. Beal, S&E-QUAL-ARA

19. SECURITY CLASSIF. (of this report) U	20. SECURITY CLASSIF. (of this page) U	21. NO. OF PAGES 78	22. PRICE NTIS

MSFC - Form 3292 (May 1969)

Page Intentionally Left Blank

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES (Continued)

TECHNICAL MEMORANDUM X-64706

ASSESSMENT OF AND STANDARDIZATION FOR QUANTITATIVE NONDESTRUCTIVE TESTING

By

Robert W. Neuschaefer and James B. Beal

SUMMARY

This document assesses present capabilities and limitations of NDT as applied to aerospace structures during design, development, production, and operational phases. This will help determine what useful data (both quantitative and qualitative) may now be provided for (1) stress analysis and fracture mechanics applications, (2) changes, in materials, fixtures, processing, or structures in design or manufacturing phases, which may be required for optimum NDT interrogation and quantitative assessment of structural integrity, (3) the selection of the optimum NDT method or combination of methods with the necessary reference standards, and, (4) planning of future research requirements due to lack of NDT assessment capabilities in certain areas.

This assessment considers two material systems which are, (1) the metal alloy systems, and, (2) bonded composites (honeycomb structures and fiber reinforced composites). The selection of these materials is based on the knowledge that they are presently applied in active NASA programs or are strong contenders for future use. Each of the two systems of materials are discussed individually due to the significant variations in defect types, NDT approaches and variations in the analytical state-of-the-art for each type.

Much qualitative information is available regarding which NDT methods are the most likely candidates for the detection of specific types of defects for each class of material. This data has been summarized from recent literature and in-house information and presented herein along with a description of those structures for which quantitative information has been obtained. Examples in tabular form have been provided in certain areas.

NDT techniques discussed and assessed in this document are radiography, ultrasonics, penetrants, thermal, acoustic, and electromagnetic.

The shift in operational requirements for NASA in the post-Apollo period, from lunar exploration to extensive earth orbital operations at the lowest possible cost, has dictated the requirement for reusable space vehicles. The severe operational requirements have resulted in highly efficient design concepts. This increases the need for quantitative NDT structural integrity assessment of selected components; thus, information on flaw detection limits can be used for fracture control.

Quantitative data is sparse and incomplete; therefore, obtaining statistically reliable flaw detection data must be strongly emphasized.

SECTION I. INTRODUCTION

The objective of this document is to assess present capabilities and limitations of NDT as applied to aerospace structures during design, development, production, and operational phases. This will determine what useful data (both quantitative and qualitative) may now be provided for (1) stress analysis and fracture mechanics applications, (2) changes, in materials, fixtures, processing, or structures in design or manufacturing phases, which may be required for optimum NDT interrogation and quantitative assessment of structural integrity, (3) the selection of the optimum NDT method or combination of methods and necessary reference standards, and (4) planning of future research requirements due to lack of NDT assessment capabilities in certain areas.

During the past several years there have been a number of structural failures in pressure vessels which occurred during proof testing or subsequently during checkout or storage (references 1 and 2). Intensive studies in the field of fracture mechanics and metallurgy and non-metallic materials have resulted in a wealth of data. This high level of knowledge may now be practically applied to the accurate prediction of the behavior of structural materials under cyclic, static, or sustained stress loading when they contain material discontinuities. The actual maximum flaw size can be measured only by nondestructive testing methods. For many alloys, of high yield strength, the critical crack size is frequently small, and depending upon location or orientation, may or may not be found by current nondestructive testing methods. It should be pointed out that present NDT methods do not always give an accurate measurement of flaw size. NDT is, at present, inadequate for many purposes -- fracture control being the most serious, but not the only area.

In this assessment we have considered two systems of materials:

1. The Metal Alloy Systems

2. Bonded Composites (Honeycomb Structures and Fiber Reinforced Composites).

The selection of the above materials is based on the knowledge that they are presently applied in active NASA programs or are strong contenders for future use. Each of the two systems of materials will be discussed individually due to the significant variations in defect types, NDT approaches, and variations in the analytical state-of-the-art for each type. It should be noted that it is possible that a reliable flaw-tolerant

2

conventional material or system of materials may be superior in weight and cost to advanced ultra-high strength concepts which may require large safety factors because of lack of quantitative NDT data or interrogation limitations of NDT techniques.

The following deficiencies in present NDT technology (reference 2) are discussed in detail within this document:

1. The potential of presently available NDT techniques is frequently not realized when applied to the problem of finding crack-flaws in actual hardware.

2. No generally recognized standards exist which permit judgement of the actual precision of a particular NDT technique, nor is there any general agreement as to how NDT operators should be qualified.

3. Frequently, the potential value of NDT techniques is compromised by a lack of inspectability of the finished hardware.

4. The development of NDT techniques for composite structures is in an embryonic state.

The following criteria were established and applied to determine the validity of quantitative data utilized in this document:

1. The simulated and natural defects analyzed must have been described in detail and they must have been relevant to all those expected in actual hardware.

2. The lower detectability limits of the particular techniques must have been specified.

3. A positive destructive or other analytical method must have been applied to provide corroboration of NDT response with defect characteristics.

4. All test conditions that could influence practical application of the data, such as special tooling, environmental conditions, surface roughness, and part size and geometry, must have been defined and documented.

Much qualitative information is available regarding which NDT methods are the most likely candidates for the detection of specific types of defects for each class of material. This data has been summarized

from recent literature and in-house information and is presented herein along with a description of those structures for which quantitative information has been obtained. Examples in tabular form have been provided which serve to illustrate the lack of quantitative information available in certain areas.

NDT techniques discussed and assessed in this document are radiography, ultrasonics, penetrants, thermal, acoustic, and electromagnetic.

The shift in operational requirements for NASA in the post-Apollo period, from lunar exploration to extensive earth orbital operations at the lowest possible cost, has dictated the requirement for reusable space vehicles. The severe operational requirements have resulted in highly efficient design concepts. The exposure of these structures to environmental and operational loads, which are difficult to accurately predict and simulate at the present time, decreases the confidence which may be placed in structural load testing and increases the need for quantitative NDT structural integrity assessment of selected components. Also, the justification for obtaining quantitative NDT data is that there are virtually no statistically reliable flaw detection data for various NDT methods, and a suitable fracture control program will require this type of data.

SECTION II. DESIGN REQUIREMENTS

The conventional design concepts for previous space vehicles utilized the factor of safety (FS) as a measure of the reliability of the design concept. This FS is normally expressed as:

$$FS = \frac{\sigma ut}{\sigma w}$$

where

$$\sigma ut = \text{ultimate tensile strength}$$

$$\sigma w = \text{working stress}$$

However, this estimate is valid if, and only if, the structure is free from flaws, or takes into account the existence of flaws as well as other uncertainties. Previous NASA experience with the 260 inch solid motor case failure and the loss of an SIVB LH_2 - LOX tank during post manufacturing proof test has demonstrated the folly of inadequate NDT.

Structural failures have prompted the designer to incorporate crack tolerance calculations in design. This has been accomplished through the application of linear elastic mechanics. A relationship exists which relates failure stress (σF), a flaw shape and load parameter (α), the plain strain fracture toughness (K_{Ic}), and the flaw length $(2c)$. One such relation, for a surface flaw, is defined as (reference 3):

$$\sigma F = \alpha K_{Ic} (c)^{-1/2}$$

To utilize such an equation for assessment of structural reliability, the designer must have (1) a valid estimate of K_{Ic} and (2) a valid estimate of flaw size limits which, at the present time, are principally obtained from proof test logic.

o Programs are currently underway within NASA to develop valid K_{Ic} values for materials of interest using the statistical methods applied in MIL-HBK-5. Table I of NASA SP-8040, "Fracture Control of Metallic Pressure Vessels", contains experimentally obtained threshold stress-intensity values for materials and environments encountered in aerospace pressure vessels. However, no NASA-wide validation of NDT methods has been undertaken. Section IV, Standardization Concepts, and the Appendix of this document provide the ground work for establishment of such an NDT evaluation.

SECTION III. QUANTITATIVE NDT STATE-OF-THE-ART

Flaws may develop during the production of structural raw materials (while the material is undergoing various fabrication processing stages) during joining and structural assembly, while being functionally tested, and while in operational service.

In qualitative NDT discontinuities (all variations, including flaws) can be detected in a material or structure and some characteristics determined, but critical measurements and sometimes positive identification of a flaw are lacking for determination of effects on strength and ultimate use.

Detection and measurement of discontinuity size, location, orientation, and characteristics are required for a suitable quantitative evaluation. The timely and proper application of NDT methods which provide this type of information will result in significant schedule and cost savings to design, manufacturing, and using functions. Current technology is not considered adequate to measure many types of small discontinuities, nondestructively and quantitatively, as indicated in this document. The use of more than one NDT evaluation method is often required for complete quantitative information. Also of

major importance are qualified NDT personnel, calibrated equipment, and suitable test standards representing design limits for defects which may occur.

A. METAL ALLOY SYSTEMS

1. MATERIALS

Metals considered in this assessment were aluminum, steel, and titanium alloys (table 1) which were originally ingots or castings.

2. PROCESSING AND FABRICATION

a. <u>Castings</u>. Gas holes may result in castings due to the use of green cores or sand molds, gas in solution in the metal, or turbulence during pouring of the metal. Shrink porosity and shrinkage cavities result from insufficient metal. Inclusions result when undesired material is trapped in the casting. Cold shuts result when a cooled stream of metal meets an opposing stream in a mold and the two streams do not fuse because the metal has overcooled. Cracks result from thermal stresses or poor design of mold or component.

b. <u>Forging</u>. Forging at too low a temperature may produce bursts (ruptures) that may be wholly internal or which may occur at the surface. Flakes are internal ruptures that result when the metal is cooled too rapidly through a certain temperature range. Dissolved gases contribute to this occurrence. Forging laps are irregular in contour and are at right angles to the metal flow. They are folds of metal that are forged into the surface.

c. <u>Sheet and Plate Material</u>. The material thickness may not be to specification due to improper controls during rolling. Laminations result from shrinkage, inclusions, or blowholes in the ingot being rolled into flattened defects during processing.

d. <u>Weldments</u>. Lack-of-fusion (LOF) to the weld joint sidewall or to another bead in a multipass weld results from insufficient heat or the presence of oxide or slag. Lack-of-penetration (LOP) results when the joint is not properly filled with the cast weld metal as a result of insufficient heat or improper joint preparation. LOP is present at the bottom of a one-sided weld and at the center of a two-sided weld. Cracks result from internal stresses caused by shrinkage upon cooling of the weld if the welding system or materials are inadequate. Tungsten inclusions result when the tungsten electrode that supports the arc in inert welding comes in contact with the weld metal. Gas porosity results from many factors including poor cleaning or poor quality of the parent metal. Slag or oxide inclusions result when there is improper cleaning between passes.

Table I. Validated NDT Quantitative Assessment Capabilities for Metal Alloys (Sheet 1 of 3)

DISCONTINUITY	MATERIAL	NDT METHOD	SOURCE OF TECHNICAL INFORMATION	CAPABILITY	LIMITATIONS	COMMENTS
HEAT TREAT	STEEL GRADE C-12 AND OTHER DEEP HARDENING GRADES	ULTRASONIC ATTENUATION EFFECTIVELY USED TO GRADE MATERIAL TO SPECIFICATION ASTM-A217	⑦	APPLICABLE TO DEEP HARDENING STEELS (SOLUTION-HEAT-TREATMENT). QUENCH TO BAINITE OR MARTINSITE; TEMPER REVEALS INPROPER PROCEDURE SUCH AS OVERHEATING (TO 25°F) IN TREATMENT. MASS PHYSICAL PROPERTIES DETERMINED.	APPLICABLE TO DEEP-HARD STEELS. PAST HISTORY MUST BE KNOWN. IF HEATED ABOVE AC 3 TEMPERATURE PRIOR TO QUENCH WILL OBTAIN AMBIGUOUS RESULTS, PURELY EMPIRICAL, MUST DEVELOP FOR EACH ALLOY AND HEAT TREATMENT.	MASS PROPERTIES (PHYSICAL) REVEALED THE DEGREE OF ULTRASONIC ATTENUATION WAS USED TO DETECT AN ALLOY STEEL WHICH WAS IMPROPERLY HEAT TREATED. A "GO-NO-GO" TEST WHICH WAS METALLOGRAPHICALLY SUBSTANTIATED.
HEAT TREAT	2014 ALUMINUM ALLOY	EDDY CURRENT ANALYSIS-STRENGTH LEVEL OF 2014 T6 VS CONDUCTIVITY AT PROPER AND IMPROPER HEAT CYCLES	⑧	INDICATES TENSILE STRENGTH WITHIN 5 PERCENT, IF NORMAL QUENCH AND AGE. OVERHEATED (FIRE DAMAGE) RESOLUTION. MASS PHYSICAL PROPERTIES DETERMINED	SOLUTION HISTORY MAY GIVE AMBIGUOUS RESULTS. PAST HISTORY HEAT TREATMENT MUST BE KNOWN IF RE-SOLUTION HEAT TREATMENT OR GROSS OVER-HEAT (ABOVE APPROXIMATELY 700°F) MUST BE USED IN CONJUNCTION WITH HARDNESS TESTING	MASS PROPERTIES (PHYSICAL) REVEALED SUFFICIENT DATA PRESENTED (IN GRAPH FORM) TO ALLOW THE DETERMINATION, BY CONDUCTIVITY MEASUREMENT, OF THE ULTIMATE STRENGTH OF 2014 ALUMINUM. SUFFICIENT DATA WAS ALSO PRESENTED WHICH WOULD ALLOW THE DETERMINATION OF THE HEAT CYCLE THE PART HAD EXPERIENCED.
HIGH TEMPERATURE HYDROGEN ATTACK	ASTM-A201, GRADE B	ULTRASONIC ATTENUATION - DETECTION OF DAMAGE PRODUCED IN STEEL BY HIGH TEMPERATURE HYDROGEN ATTACK	⑨	± 0.1 INCH	NOT USED FOR THIN WALL VESSELS. OUTSIDE ACCESS REQUIRED. TANK WALLS ONLY	TEST RESULTS SHOW THAT ULTRASONIC ATTENUATION CAN BE USED AS A "GO-NO-GO" GAGE TO DETECT HIGH TEMPERATURE HYDROGEN ATTACK (NOTE 2)
THICKNESS MEASUREMENT	ALUMINUM, STEEL, TITANIUM	ULTRASONIC RESONANCE - 0.01 INCH T TO 10.0 INCH T	BRANSON INSTRUMENTS COMPANY	0.09 TO 0.49 INCH (GREATER THICKNESS FEASIBLE). 94 PERCENT MEASUREMENT WITHIN ± 0.002 INCH; 100 PERCENT, WITHIN ± 0.004 INCH	SINGLE POINT MEASUREMENT ONLY. METALS BADLY FLAWED (INTERNAL VOIDS) MAY GIVE INCORRECT MEASUREMENTS. PREFER UNIFORM THICKNESS	ALLOY HISTORY MUST BE KNOWN. CONSERVATIVE CAPABILITY. SEVERAL AVAILABLE INSTRUMENTS. CONVENTIONAL ULTRASONIC REFLECTOSCOPE MEASURES HEAVY PLATE (ABOVE 0.5 INCH) TO WITHIN 1 PERCENT NOTE: STATISTICAL CORRELATION ON THIS DATA HAS NOT BEEN ACCOMPLISHED.
POROSITY	ALUMINUM ALLOY 2014-T6 WELDMENTS	RADIOGRAPHY	⑩	2-2T 100 PERCENT OF TIME, (COMPLIES WITH MIL-STD-453)	ONLY 50 PERCENT DETECTABILITY ON 0.003 HOLE IN 2 PERCENT PENETRAMETER.	POORER ABILITY TO DETECT POROSITY THAN COMMONLY BELIEVED. WILL MISS MUCH MICROPOROSITY. WELD BEAD FLUSH MACHINED TO 63 RMS TO ELIMINATE WELD RIPPLE AND SURFACE DEFECTS. X-RAY IS THICKNESS SENSITIVE. (CORRELATED WITH DESTRUCTIVE TEST) PICTORAL NATURE OF X-RAY GIVES EXCELLENT RESOLUTION OF FLAW GEOMETRY (ROUND HOLES IN FLAT PENETRAMETERS 2,3,4 AND 5 PERCENT THICKNESS) FLAT PLATE BUTT WELDS
POROSITY	ALUMINUM ALLOY WELDMENTS 0.187 THRU 1.00 INCH	ULTRASONIC DELTA TECHNIQUE (AUTOMATED)	⑫	DETECTS 92 PERCENT OF POROSITY >0.010 INCH. 49 PERCENT OF POROSITY <0.010 INCH.	CLUSTERED SMALL POROSITY MAY COMBINE TO YIELD RETURN SIGNAL. THIS TYPE RETURN MAY MASK OTHER SIGNAL RETURNS. DOES NOT GIVE GOOD SHAPE, POSITION OR ORIENTATION.	GOOD SENSITIVITY IN DETECTING POROSITY NOT CAPABLE OF SHAPE RESOLUTION DUE TO LONG WAVELENGTH, DENSE, CLUSTERED, MICRO-POROUS AREAS MAY GIVE COMMON RETURN. WELD BEAD FLUSH MACHINE TO 63 RMS TO ELIMINATE WELD RIPPLE. NOT SENSITIVE TO THICKNESS OVER RANGE STUDIED (CORRELATED WITH DESTRUCTIVE TESTS) ("NATURALLY" OCCURRING DEFECTS IN ALUMINUM WELDS EVALUATED IN THIS PROGRAM, PLUS FLAT-BOTTOM DRILLED HOLES.) BUTT WELDS
INTERNAL CRACKS	ALUMINUM ALLOY WELDMENTS 0.187 THRU 1.00 INCH	ULTRASONIC DELTA TECHNIQUE (AUTOMATED)	⑬	DETECTS 90 PERCENT OF ALL CRACKS AND CRACK-LIKE DEFECTS IN MATERIAL THICKNESS OF 0.150 INCH TO 1.000 INCH AND WHERE CRACKS EXCEED 0.0001-INCH WIDE BY 0.033-INCH DEEP BY 0.060-INCH LONG	WELD BEADS MUST BE SCARFED FLUSH TO WITHIN APPROXIMATELY 0.020-INCH OF FLUSH WITH BLENDED EDGES, DEPENDING ON PROBE (WHEEL OR MANUAL); NOT HIGHLY EFFECTIVE IN INDICATING SHAPE AND ORIENTATION OF FLAWS.	METHOD RELATIVELY INSENSITIVE TO THICKNESS OF MATERIAL TESTED. METHOD NOT DEPENDENT UPON SCAN SPEED OR ORIENTATION OF THE TRANSDUCER SYSTEM TO THE WELD, HOWEVER, CLOSELY SPACED FLAWS MAY GIVE COMMON RETURN. INSENSITIVE TO PART GEOMETRY WHEN IMMERSION TESTING. BUTT WELDS [NOTE 1]
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	STEEL-ALLOY WELDMENTS, TIG AND SUBMERGED ARC WELD. 18Ni (200), 18Ni (250) 9Ni-4Co- .25C, 12 Ni-5Cr- .3 MO, AND 5 Ni-MO-V.	RADIOGRAPHY	④	RADIOGRAPHY CONSISTENTLY MISSES CRACKS 0.063 BY 0.155 INCH AND SMALLER FLAWS AS LARGE AS 0.21 BY 0.60 INCH WERE MISSED	NOT EFFECTIVE IN DETECTING TIGHT CRACKS SUCH AS FATIGUE CRACKS. ONLY CRACKS FOUND WERE THOSE COVERED BY WELD PASS WHERE HEAT OPENED CRACK, AND PASS HELD IT OPEN.	CRACKS MUST BE PARALLEL TO X-RAY BEAM FOR OPTIMUM DETECTABILITY. BUTT WELD. MACHINE TO 125 RMS, OR BETTER

GENERAL NOTE: CAPABILITIES LISTED WERE ESTABLISHED UNDER CONTROLLED LABORATORY CONDITIONS.

NOTE 1: ULTRASONIC AND PENETRANT TESTS ARE GREATLY ENHANCED IN CAPABILITY BY TENSILE PRELOADING TO NEAR YIELD OR TESTING UNDER LOAD TO AT LEAST 50 PERCENT OF YIELD CONDITIONS.

NOTE 2: THIS METHOD NOT FOR THIN (LESS THAN 0.5-INCH WALL) VESSELS. THIS TEST IS PROBABLY VALID FOR THE GENERAL CLASS OF LOW ALLOY OR CARBON STEEL PRESSURE VESSELS, BUT REQUIRES ADDITIONAL VERIFICATION.

Page Intentionally Left Blank

Table 1. Validated NDT Quantitative Assessment Capabilities for Metal Alloys (Sheet 2 of 3)

DISCONTINUITY	MATERIAL	NDT METHOD	SOURCE OF TECHNICAL INFORMATION	CAPABILITY	LIMITATIONS	COMMENTS
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	STEEL-ALLOY WELDMENTS, TIG AND SUBMERGED ARC WELD, 18Ni-(200), 18Ni (250) 9Ni-4CO- 25C, 12Ni-5Cr-.3 MO, AND 5Ni-MO-V.	ULTRASONIC	④	CRACKS DOWN TO 0.30-INCH DEEP AND 0.75-INCH LONG DETECTED; BUT REQUIRES HIGHER THAN NORMAL SENSITIVITY.	INDICATED SIZE LIMITATION, WILL BE ABOVE CRITICAL SIZE FOR HIGHLY STRESSED STRUCTURES.	SIZE LIMITATION OF DETECTABILITY WILL MISS SOME FLAWS. SHOP TECHNIQUE MAY NOT BE ABLE TO REACH STATED LIMITS.
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	GRADE D6AC ALLOY STEEL	PENETRANT	⑤	SURFACE CRACK 0.021-INCH LONG BY 0.00003-INCH WIDE AND 0.001-INCH DEEP DETECTED	SURFACE SMEARS REQUIRE ETCHING. VISUAL ACCESS REQUIRED. SURFACE DEFECTS ONLY.	DEFECT MUST FILL WITH PENETRANT. FLUORESCENT MOST SENSITIVE TYPE. [NOTE I]
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	GRADE D6AC ALLOY STEEL	RADIOGRAPHY	⑤	SURFACE CRACK 0.092-INCH LONG, 0.0001-INCH WIDE, AND 0.019 INCH DEEP	BORDERLINE AT THIS SIZE. OPERATOR KNEW WHERE CRACK WAS- DEPTH NORMAL TO SURFACE OF 0.226-INCH THICK PLATE.	METHOD NOT CAPABLE OF DETECTING CRACKS PARALLEL TO SURFACE. UNLESS CRACK WIDTH IS LARGE ENOUGH TO CREATE DENSITY CHANGE OF >2 PERCENT OF THICKNESS
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	GRADE D6AC ALLOY STEEL	ULTRASONIC SHEAR WAVE (ANGLE BEAM)	⑤	SURFACE CRACK 0.051-INCH LONG, 0.00003-INCH WIDE, AND 0.003 INCH DEEP	ORIENTATION BETWEEN 60° AND 90° TO DIRECTION OF CRACK.	IMMERSION TECHNIQUE NATURALLY OCCURING SURFACE CRACK. DEPTH NORMAL TO SURFACE OF 0.210-INCH PLATE [NOTE I]
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	ALUMINUM ALLOYS 2014-T6 2219-T87 0.020-INCH THICK 0.125-INCH THICK	PENETRANT	⑥	SEE TABLES 3 & 4 & NOTES 3, 4, 5, & 6	SURFACE SMEARS REQUIRE ETCHING. VISUAL ACCESS REQUIRED. SURFACE DEFECTS ONLY.	FLUORESCENT PENETRANT. SENSITIVITY WILL BE LOWER ON THICKER MATERIAL. MOST PRECISE LENGTH INDICATION NDT METHOD. [NOTE I]
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	ALUMINUM ALLOY 2014-T6 2219-T87 0.020-0.500- & 1.000-INCH THICK	RADIOGRAPHY	⑥	SEE TABLES 3 & 4 & NOTES 3, 4, 5, & 6	CRACK MUST BE NORMAL TO SURFACE. TIGHTLY FITTED CRACKS NOT DETECTED. SPECIMEN THICKNESS LIMITS CRACK SIZE DETECTABLE	WILL NOT DETECT CRACKS RELIABLY THAT ARE NORMAL TO BEAM (OR PARALLEL TO SURFACE) UNLESS CRACK WIDTH IS LARGE ENOUGH TO CREATE DENSITY CHANGE OF >2 PERCENT OF THICKNESS.
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	ALUMINUM ALLOY 2014-T6 2219-T87 0.020-0.125-0.500- & 1.000-INCH THICK	ULTRASONIC SHEAR WAVE (ANGLE BEAM)	⑥	SEE TABLES 3 & 4 & NOTES 3, 4, 5, & 6	TIGHTLY FITTED CRACKS NOT DETECTED.	[NOTE I] WATER IMMERSION.
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	ALUMINUM ALLOY 2014-T6 2219-T87 0.125-0.500-& 1.000-INCH THICK	ULTRASONIC DELTA TECHNIQUE (AUTOMATED)	⑧	SEE TABLES 3 & 4 & NOTES 3, 4, 5, & 6	COULD NOT BE USED ON 0.020-INCH THICK SPECIMENS. DOES NOT GIVE GOOD SHAPE, POSITION OR ORIENTATION OR FLAW.	[NOTE I] WATER IMMERSION
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	TITANIUM ALLOY 5AL-2.5 Sn 6AL-4V 0.020-INCH THICK 0.125-INCH THICK	RADIOGRAPHY	⑥	SEE TABLES 3 & 4 & NOTES 3, 4, 5, & 6	CRACK MUST BE NORMAL TO SUR-FACE. TIGHTLY FITTED CRACKS NOT DETECTED. SPECIMEN THICKNESS LIMITS CRACK SIZE DETECTABLE.	WILL NOT DETECT CRACKS RELIABLY THAT ARE NORMAL TO BEAM, (OR PARALLEL TO SURFACE) UNLESS CRACK WIDTH IS LARGE ENOUGH TO CREATE DENSITY CHANGE OF >2 PERCENT OF THICKNESS
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	TITANIUM ALLOY 5AL-2.5 Sn 0.020-0.125-& 0.500-INCH THICK	PENETRANT	⑥	SEE TABLES 3 & 4 & NOTES 3, 4, 5, & 6	SURFACE SMEARS REQUIRE ETCHING. VISUAL ACCESS REQUIRED. SURFACE DEFECTS ONLY.	FLUORESCENT PENETRANT. MOST PRECISE LENGTH INDICATION NDT METHOD. [NOTE 1]

NOTE 3: PRESENT NDT TESTS ARE OF LIMITED USE FOR CRITICAL CRACK MEASUREMENTS. IMPROVED TESTING TECHNIQUES NECESSARY.
NOTE 4: FLAT, TENSILE, "DOGBONE" SPECIMENS USED.
NOTE 5: MINIMUM CRACK LENGTH (L) MUST BE USED AS REJECTION CRITERIA, AS DETERMINED FROM FRACTURE TOUGHNESS CALCULATIONS. NO ACCURATE DEFECT DEPTH (D) DETERMINATION COULD BE MADE.
NOTE 6: STANDARD STATISTICAL LINEAR REGRESSION ANALYSIS TECHNIQUES USED TO CORRELATE MEASURED NDT VALUES WITH ACTUAL DEFECT DIMENSIONS.

9

Table 1. Validated NDT Quantitative Assessment Capabilities
for Metal Alloys (Sheet 3 of 3)

DISCONTINUITY	MATERIAL	NDT METHOD	SOURCE OF TECHNICAL INFORMATION	CAPABILITY	LIMITATIONS	COMMENTS
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	TITANIUM ALLOY 5AL-2.5 Sn 6AL-4V 0.125-INCH THICK 0.500-INCH THICK	ULTRASONIC DELTA TECHNIQUE (AUTOMATED)	⑥	SEE TABLES 3 & 4 & NOTES 3,4,5, & 6	COULD NOT BE USED ON 0.500-INCH THICK SPECIMENS. DOES NOT GIVE GOOD SHAPE, POSITION, OR ORIENTATION OF FLAW.	WATER IMMERSION. [NOTE 1]
SURFACE CRACKS (EDM CUTS, FATIGUE EXTENDED)	TITANIUM ALLOY 5AL-2.5 Sn 6AL-4V 0.023-0.125-& 0.500-INCH THICK	ULTRASONIC SHEAR WAVE (ANGLE BEAM)	⑥	SEE TABLES 3 & 4 & NOTES 3,4,5, & 6	TIGHTLY FITTED CRACKS NOT DETECTED	INDICATIONS LARGER THAN CRACK SIZE. SENSITIVITY LOWER ON THICKER MATERIAL. WATER IMMERSION. [NOTE 1]

Page Intentionally Left Blank

Page Intentionally Left Blank

e. **Brazed Joints.** A cold brazed joint will result when there is alloy flow but no metallurgical bond due to poor surface cleanliness. Porosity may also occur for the same reason. The braze alloy may not flow properly because of poor joint design.

3. **OPERATIONAL SERVICE**

Defects such as fatigue cracks and grinding cracks may be present in any material as a result of service or processing activities. Other types of defects may include metallurgical conditions that jeopardize the integrity of the structure. These conditions may be improper alloy utilization or heat treatment, hydrogen embrittlement, and susceptibility to or occurrence of stress corrosion cracking.

4. **ASSESSMENT OF QUANTITATIVE NDT CAPABILITIES**

Evaluation of documented NDT data in the area of quantitative information shows considerable preliminary work accomplished with ultrasonic, radiographic, penetrant,and eddy current methods, as indicated in tables 1, 2, 3, and 4. (These tables are meant to be representative only, not all-inclusive of information available about these NDT methods.)

a. Because of the complex nature of materials, processes, and configurations inherent in metal alloy structures, complementary NDT systems are required for optimum measurement of structural integrity. In addition, reliable flaw detection limits must be established for existing NDT methods that are properly applied. Optimum performance of highly stressed hardware made from metal alloys requires continual information on mechanical properties derived from standard tests, improved structural analysis procedures, and development of nondestructive evaluation techniques suitable for detecting discontinuities smaller than design allowables.

b. The trend toward reusable space vehicles and checkout of structures in the field with little or no disassembly will require more development of NDT methods requiring access to one side only. It has been suggested in recent literature that built-in sensors for monitoring of in-flight dynamic conditions and static on-site checkout interrogation may be worthwhile. For example, information obtained during the technical survey for this document has indicated that the new area of acoustic emission analysis may provide an excellent technique for application with other NDT methods in the analysis of pressure vessel and structural integrity under both flight and ground test conditions. Reference 13 reports the correlation of stress-wave emission characteristics with fracture mechanics analysis. The integration of acoustic emission and fracture mechanics technologies provide a comprehensive approach to the assessment of flaw criticality since both

13

Table 2. Critical Crack Size and Minimum Specimen Dimensions
for Selected Materials (Reference 6 Tables IV and V)

MATERIAL	T °F	YIELD STRESS ksi	K_c ksi $\sqrt{inch}$	APPLIED STRESS ksi	a/2C	CRITICAL CRACK DEPTH, a (inch)	CRITICAL CRACK LENGTH, 2c (inch)	B THICKNESS (inch)	W MINIMUM WIDTH (inch)
AL 2014 T6	-423	81	48	73	0.1	0.117	1.177	1.000	3.53
					0.1	0.117	1.177	0.500	3.53
					0.1	0.117	1.177	0.125	3.53
					0.1	0.117	1.177	0.020	3.53
					0.3	0.167	0.5572	1.000	1.67
					0.3	0.167	0.5572	0.500	1.67
					0.3	0.167	0.5572	0.125	1.67
					0.3	0.167	0.5572	0.020	1.67
					0.5	0.261	0.5221	1.000	1.57
					0.5	0.261	0.5221	0.500	1.57
					0.5	0.261	0.5221	0.125	1.57
					0.5	0.261	0.5221	0.200	1.57
AL 2219 T87	-423	74	44	67	0.1	0.117	1.172	1.000	3.52
					0.1	0.117	1.172	0.500	3.52
					0.1	0.117	1.172	0.125	3.52
					0.1	0.117	1.172	0.020	3.52
					0.3	0.167	0.555	1.000	1.67
					0.3	0.167	0.555	0.500	1.67
					0.3	0.167	0.555	0.125	1.67
					0.3	0.167	0.555	0.020	1.67
					0.5	0.260	0.520	1.000	1.56
					0.5	0.260	0.520	0.500	1.56
					0.5	0.260	0.520	0.125	1.56
					0.5	0.260	0.520	0.020	1.56
5A1-2.5Sn-Ti	-423	210	54	189	0.1	0.022	0.222	0.500	0.66
					0.1	0.022	0.222	0.125	0.66
					0.1	0.022	0.222	0.020	
					0.3	0.031	0.105	0.500	0.31
					0.3	0.031	0.105	0.125	0.31
					0.3	0.031	0.105	0.020	0.31
					0.5	0.049	0.098	0.500	0.29
					0.5	0.049	0.098	0.125	0.29
					0.5	0.049	0.098	0.020	0.29
6A1-4V-Ti	-423	220	54	189	0.1	0.017	0.173	0.500	0.52
					0.1	0.017	0.173	0.125	0.52
					0.1	0.017	0.173	0.020	0.52
					0.3	0.024	0.0822	0.500	0.24
					0.3	0.024	0.0822	0.125	0.24
					0.3	0.024	0.0822	0.020	0.24
					0.5	0.038	0.0770	0.500	0.23
					0.5	0.038	0.0770	0.125	0.23
					0.5	0.038	0.0770	0.020	0.23

Page Intentionally Left Blank

Table 3. Summaries of Crack Data (Reference 6, Tables XXXI and XXXII)

		MAXIMUM CRACK LENGTHS POSSIBLE FOR ZERO INDICATED CRACK LENGTHS AND TEST ACCURACIES FOR THE VARIOUS NONDESTRUCTIVE TESTING TECHNIQUES (USING ±3σ LIMIT)*								MAXIMUM CRACK DEPTHS POSSIBLE FOR ZERO INDICATED CRACK DEPTHS AND TEST ACCURACIES FOR THE ULTRASONIC SHEAR AND DELTA TESTING TECHNIQUES (USING ±3σ LIMIT)*					
		RADIOGRAPHIC		PENETRANT		ULTRASONIC SHEAR		ULTRASONIC DELTA		ULTRASONIC SHEAR (INCREMENT)		ULTRASONIC SHEAR (AREA)		ULTRASONIC DELTA	
THICKNESS	ALLOY	MCL	±3σ	MCL	±3σ	MCL	±3σ	MCL	±3σ	MCD	±3σ	MCD	±3σ	MCD	±3σ
0.020	2014 & 2219 A1	**	**	0.040	0.036	0.048	0.062	—	—	—	—	—	—	—	—
0.020	6-4 & 5-2.5 Ti	0.069	0.051	0.032	0.027	0.097	0.084	—	—	—	—	—	—	—	—
0.020	6A1-4V-Ti	—	—	—	—	0.051	0.039	—	—	—	—	—	—	—	—
0.125	2014 & 2219 A1	**	**	0.029	0.032	**	**	**	**	**	**	**	**	**	**
0.125	6-4 & 5-2.5 Ti	0.130	0.088	0.050	0.067	—	—	0.061	0.105						
0.125	6A1-4V-Ti	—	—	—	—	**	**	**	**	**	**	**	**	0.024	0.020
0.125	5A1-2.5Sn-Ti	—	—	—	—	0.092	0.070	0.057	0.081	0.034	0.015	0.033	0.024	**	**
0.500	2014 & 2219	0.458	0.237	**	**	—	—	—	—						
0.500	2014 A1	—	—	—	—	***	***	***	***	***	***	***	***	***	***
0.500	2219 A1	—	—	—	—	0.278	0.246	-0.114	0.319	**	**	**	**	**	**
0.500	6-4 & 5-2.5-Ti	**	**	0.025	0.021	**	**	0.090	0.125	**	**	**	**	**	**
0.500	6A1-4V-Ti	—	—	—	—	***	***	***	***	***	***	***	***	***	***
0.500	5A1-2.5Sn-Ti	—	—	—	—	0.153	0.073	0.158	0.125	0.069	0.042	0.083	0.058	0.099	0.090
1.000	2014 & 2219 A1	0.210	0.164	**	**	**	**	**	**	**	**	**	**	**	**

* ALL DIMENSIONS IN INCHES   ** NO CORRELATION   *** INSUFFICIENT SAMPLE

MCL - MAXIMUM CRACK LENGTH AT ZERO INDICATED LENGTH

NOTES: 1. STANDARD STATISTICAL ANALYSIS TECHNIQUES WERE APPLIED TO CORRELATE THE MEASURED NDT VALUES WITH ACTUAL DEFECT DIMENSIONS. LINEAR REGRESSION ANALYSIS TECHNIQUES WERE USED.

2. PRESENT NONDESTRUCTIVE TESTS ARE OF LIMITED USE FOR CRITICAL CRACK MEASUREMENTS. IMPROVED TESTING TECHNIQUES ARE NECESSARY IN ORDER TO ACHIEVE BETTER MEASUREMENT ACCURACY.

Page Intentionally Left Blank

TABLE 4. CRACK DEFINITION OF NDT TECHNIQUES (Reference 6)

	Crack Length Detected by N.D.T. Technique							
	Fluorescent Penetrant (Inches)				Radiography (Inches)			
ALLOY \ Thickness of Specimen	0.020	0.125	0.500	1.000	0.020	0.125	0.500	1.000
AL 2014 - T6	0.087*	0.046*	—	—	0.087*	—	0.554*	0.550*
AL 2219 - T87	0.125*	0.064*	—	—	0.125*	—	+0.323	0.473*
T1 5AL - 2.5 SN	0.062*	0.054*	0.062*	—	+0.075	+0.200	—	—
T1 6AL - 4V	0.067*	0.054*	0.095*	—	+0.082	+0.062	—	—

	Crack Length Detected by N.D.T. Technique							
	Ultrasonic Shear Wave (Inches)				Ultrasonic Delta (Inches)			
ALLOY \ Thickness of Specimen	0.020	0.125	0.500	1.000	0.020	0.125	0.500	1.000
AL 2014 - T6	0.087*	0.046*	0.554*	0.550*	—	0.046*	0.554*	0.550*
AL 2219 - T87	0.125*	0.064*	0.299*	0.473*	—	0.064*	0.299*	0.473*
T1 5AL - 2.5 SN	0.062*	0.054*	0.062*	—	—	0.054*	0.062*	—
T1 6AL - 4V	0.067*	0.054*	0.095*	—	—	0.054*	0.095*	—

* Smallest crack length existing in specimens tested -- not the minimum detectable flaw size.

\+ Minimum detectable flaw size.

NOTE: Above data are from surface fatigue cracks which were extended from EDM cuts.

describe and analyze phenomena occurring at stress concentrations, such as those that exist in the region of a flaw. This technology has been successfully applied to the detection and location of propagating flaws in structures, both during testing and under service conditions. In such applications, the stress waves created by crack extension are detected and analyzed to determine the start of crack instability and, at the same time, triangulated to the source of the emissions using seismic techniques. In addition, it has been previously demonstrated that certain stress wave emission characteristics can be parametrically related to the stress intensity factor determined for a given flaw size, shape, and stress level.

c. Assessment Capabilities Discussion for Metal Alloys

(1) Summary of NDT Data. The following conclusions may be drawn from an analysis of Table 1 in light of the requirements of fracture mechanics to provide accurate quantitative information regarding flaw size, location, geometry, and orientation:

(a) The available data illustrates that the standard radiographic technique, as it is now employed (two percent thickness resolution at 90 degrees to the material surface), has severe limitations, particularly with regard to the detection of cracks and LOP and LOF. The radiographic method is most advanced, however, in providing quantitative information regarding flaw location, sizes, shapes, and orientation when special techniques such as multiple angle shots are employed. Improvement of radiographic techniques continues in such areas as electronic enhancement of radiographs and use of radiographically opaque tracer coatings (such as copper) on aluminum joint edges before welding to show tight LOP conditions.

(b) Delta ultrasonics is one of the more sensitive methods for detection of cracks and crack type defects. The present state-of-the-art is limited to providing information regarding location along the axis of a weld or from the edge of a forging and assessing the approximate size of the defect; however, it cannot determine whether a linear indication is a crack, LOP, or LOF in its orientation or depth within the part. Further research may provide more definitive information. (See tables 1, 3, and 4.)

(c) Liquid penetrant methods can provide the most accurate determination of the length of surface cracks. Quantitative information is available from tables 1, 3 and 4; and reference 6.

(2)   Structural Analysis Applications. It has been determined that there are several structural problems which have been solved and for which some quantitative data exists. The examples noted in Table 1 include thickness determination of structures, determination of heat treat condition, detection of fatigue cracks, and determination of lower limits for radiographic detection of simulated cracks.

Though not documented, it is considered feasible, within the present state-of-the-art, to sort the commonly used structural alloys and determine their temper using thermoelectric and phase-sensitive eddy current devices in combination. It is also considered feasible, within the state-of-the-art, to detect high temperature hydrogen attack and provide a quantitative assessment of the degree of structural degradation.

Qualitative work has been reported (reference 11) in the detection of titanium hydride using neutron radiography. General Electric Company and Atomics International have also performed investigations in this area.

B.   BONDED COMPOSITES - HONEYCOMB STRUCTURES AND FIBER REINFORCED COMPOSITES

In addition to the types of metallic structures and simple configurations wherein a single alloy is utilized and joined by welding, bonding, brazing, or fastening there exist the important classes of composite materials. Among the almost infinite variety of materials and combinations, those most commonly used in aerospace applications will be discussed herein and will serve to illustrate some basic philosophies which may be applied to other structures. This discussion covers two basic classes of composites, bonded honeycomb and bonded filamentary structures. The composites may be metallic, nonmetallic, or a combination of both.

1.   MATERIALS

a.   Bonded honeycomb material combinations and materials considered in this assessment were as follows:

Metal facesheets (aluminum) and a metal honeycomb core (aluminum)

21

- Metal facesheets (aluminum) and a nonmetal
  honeycomb core of heat resistant phenolic (HRP)

- Nonmetal facesheets (laminates of glass, boron,
  or graphite fibers in an epoxy matrix) and a metal
  honeycomb core (aluminum)

- Adhesive (used as a bonding agent between adjacent
  surfaces, such as in laminates, and facesheet to
  core applications -- generally comes in sheet form
  and must be kept under refrigeration)

    b.   Fiber reinforced composites considered in this assessment
were laminates containing the following materials:

- Filaments of glass, boron, or graphite fibers

- Matrix of epoxy resins in which the filaments are
  embedded to form tape or sheet material for subse-
  quent layup into laminates of required thickness.

    c.   Many discontinuities can exist within the basic raw
materials; but, since the various structural components of bonded honeycomb
undergo several inspections prior to assembly, failures of materials are
infrequent.   The tape or sheet material laid up to form a multilayer laminate
is inspected separately; but, in this type of material local areas containing
density variations, poor fiber spacing and misalignment, and broken fibers
can occur and miss detection.   These same conditions can also occur during
fabrication of the laminate.

2.   PROCESSING AND FABRICATION

    a.   Bonded composites are fabricated by careful manual
layup of cleaned and preformed components.   Pressure is then applied
by press or autoclave at an elevated temperature until the adhesive or
bonding matrix flows and cures properly between laminates or facesheet
and core.

    b.   Composites are most useful in flat configurations or
simple curvatures and are primarily valued for strength, lightweight, and
insulative characteristics.   Joints and fasteners must be carefully
designed and thoroughly accessible for NDT evaluation.   Laminates can
be laid up and cured for later use as facesheets on honeycomb cores or
selective reinforcements on stressed primary metal structures.   The
new advanced filamentary composites (boron or graphite) have more

desirable strength-to-weight ratio characteristics than metal composites; therefore, their applications and methods for NDT evaluation are rapidly being pursued.

c.   The greatest number of structural failures and problems have occurred because of human error in poor control of cleanliness, raw material, material and adhesive storage, layup, and bond cure processes. The most common types of defects and variations in bonded honeycomb structures are debonds, porosity, inclusions, lack of adhesive, crushed core, bond strength (adhesive and cohesive), core splice integrity, and delamination in nonmetal laminate facesheets. The most critical of these are debond, delamination, and bond strength. The most common types of defects and variations in laminates are density, porosity, delamination, and filament-to-resin volume ratios.

3.   OPERATIONAL SERVICE

a.   Bonded honeycomb structures have applications for interstage cylinders, instrument attach plates, tank wall and bulkheads, internal or external cryogenic insulation, solar cell attach panels, and external skin panels.

b.   The current applications for fiber-reinforced composites are thrust structure beams, trusses, selective reinforcement of stress points (caps and stiffeners), and structure external skin panels, where applicable. As the cost of materials decrease and confidence in repeatable design characteristics and inspectability increase, this type of composite. (in honeycomb or laminate) will gradually replace conventional skin and stringer and tank structures in selected applications.

c.   A number of conditions requiring NDT evaluations may arise during operational use of laminate structures. These conditions could include internal layer delamination, debond from substrate, entrapped moisture, damage and repair evaluation, and the need for NDT reevaluation during refurbishment of flight hardware.

d.   The operational life of a bonded honeycomb structure is dependent upon material characteristics, bond strength, debond (or delamination) growth rates, and the critical area of debond at the operating stress level. At the present state of NDT development, no applied methods exist for determination of adhesive bond strength. Acoustic emission of adhesive bond failure signals, during a specified stress loading, has possibilities for location of weak bond areas; however, more research and development (R&D) efforts are required. The amount and type of

stress applications are definite limitations with this potential method. With other NDT techniques, an estimate of internal structural variations and discontinuity size, shape, location, and orientation can be defined so that feedback of information to design, fabrication, and process functions can be made, structural reliability improved, and realistic NDT test standards developed.

e. The operational life of laminate structures of the types described depends upon the material elastic properties and any debond that may occur at the operating stress level. It is now possible to apply the capabilities of NDT to laminates containing boron or graphite filaments in a plastic matrix and fully characterize their elastic properties, attempt estimates of ultimate properties, and properly detect gross defects.

4. ASSESSMENT OF QUANTITATIVE NDT CAPABILITIES

The available NDT data were analyzed, corrolated, and tabulated to permit visibility of the quantitative assessment capabilities of various NDT methods. This information is presented in tables 5, 6, and 7. Assessments of the quantitative NDT capabilities for composite structures were made separately for the two major forms of composites, bonded honeycomb and bonded filamentary structures.

a. Because of the complex nature of materials, processes, and configurations inherent in composite structures, complementary NDT systems are required for optimum measurement of structural integrity. Because of the large variety of composite combinations that can be tailored for particular structural applications, qualitative data are often the only information available from which a suitably definitive quantitative program can begin. The rational design of highly stressed hardware made from composites requires additional information on mechanical properties derived from standard tests, better structural analysis procedures, and the development of nondestructive evaluation techniques suitable for detecting manufacturing flaws.

b. Evaluation of documented NDT data in the area of quantitative information shows considerable work accomplished with ultrasonic velocity, thermal, and gamma radiometric methods. Because two of these three methods now require backside access, additional data will have to be obtained from NDT methods requiring access to one side only. Therefore, it is imperative that an evaluation of the quantitative assessment capabilities of the NDT method discussed be performed for the structures to be developed in-house or by contractor. Determinations would then be made if the acceptance and rejection limits to structural

Table 5. NDT Capabilities for Composite Structures

	SONIC	ULTRASONIC				THERMAL		ACOUSTIC	RADIOGRAPHY	
	EDDY SONIC (18)	IMPEDANCE (18)	PULSE ECHO	THRU XMISSION	VELOCITY (14)(15)	INFRA-RED	LIQUID CRYSTAL (16)	ACOUSTIC EMISSION (17)	X-RAY	GAMMA (15) RADIOMETRIC (14)
ADVANTAGES X APPLIES TO LAMINATES AND COMPOSITE STRUCTURES. # APPLIES ONLY TO NONMETAL LAMINATES	- ONLY ONE SIDE ACCESS REQD - NO COUPLANT - NON-CONTACTING IF DESIRED - AUTOMATED C-SCAN	X - METAL AND NONMETAL STRUCTURE - ONLY ONE SIDE ACCESS REQD - AUTOMATED C-SCAN	X - METAL AND NONMETAL STRUCTURE - ONLY ONE SIDE ACCESS REQD - AUTOMATED C-SCAN	X - HIGHEST SENSITIVITY TO DEFECTS OF U/S METHODS - AUTOMATED C-SCAN	# - COUPLANTS NOT NORMALLY REQD	X - NONCONTACT - - DIRECT VIEWING - TEMP. RANGE VARIABLE - RAPID EVAL, - PORTABLE - MIN TRAINING REQD -80 X MAG. TO INFINITY STRUC. SIZE -DYNAMIC MONITORING OF STRUC. IN TEST OR OPERATION	X - SIMPLE, EASY TO APPLY, EASY TO EVAL - - FILM OR PAINT - - COLOR = TEMP., - - PORTABLE, - - TEMP. RANGE VARIABLE - - DIRECT VIEWING IN COLOR - BEST MATL COMB FOR EVAL IS METAL F/S WITH METAL HONEYCOMB CORE, TITANIUM F/S WITH AL CORE. -DYNAMIC MONITORING OF STRUC. IN TEST OR OPERATION	X - DETECTS WEAK ADHESIVE BONDS AND CAN LOCATE W/ TRIANGULATION, IF REQD - PORTABLE, - - SIMPLE TO OPERATE, - NOT CONFIG. SENSITIVE - NO COUPLANT - ONLY METHOD DISCOVERED FOR ADHESIVE BOND STRENGTH DATA -DYNAMIC MONITORING OF STRUC. IN TEST OR OPERATION	X - NONCONTACT - NO COUPLANTS, - PORTABLE-CANBE AUTOMATED, PERM RECORD, - SENSITIVE TO DENSITY CHANGES - EXCELLENT RESOLUTION OF ANY MATL VARIATION EXCEEDING 2% OF THICKNESS/ DENSITY CHANGE	# - BEST METHOD FOR QUANTITATIVE DATA EVAL TO DATE WHEN COMBINED WITH U/S VELOCITY ANALYSIS - SIMPLE
LIMITATIONS X APPLIES TO LAMINATES AND COMPOSITE STRUCTURES. # APPLIES ONLY TO NONMETAL LAMINATES	- METAL F/S REQD	X - COUPLANT REQD	X - COUPLANT REQD	X - COUPLANT REQD - BACKSIDE ACCESS REQD	# - BACKSIDE ACCESS REQD	X - THICKNESS SENSITIVE- - STRUCTURAL HEATING AND COOLING REQD - BACKSIDE ACCESS REQD FOR H/C	X - APPLIED MANUALLY AND VISUALLY EVALUATED (OPERATOR SENSITIVE) - SURF. CONTACT. BACKSIDE ACCESS REQD - FOR H/C - THICKNESS SENSITIVE - BRIGHT LIGHTS, HEAT & COOL REQD-WORST MATL COMB FOR EVAL IS AL METAL F/S WITH NONMETAL H/C CORE.	X - MATLS, DENSITY, AND T LIMIT APPLICATION - BONDLINE STRESS REQD - NO DEFECT IDENTIFICATION, ONLY LOCA-TION, IF 3 OR MORE TRANSDUCERS USED (THEN COMPUTER REQD) - NEW METHOD, NEEDS MORE DEVELOPMENT IN THIS AREA - MAY BE LIMITED TO SMALL STRUCTURE - NDT STDS NOT APPLICABLE, REQS SAMPLE STRUC. FAILURE & SIGNAL COMPARISON	X - HIGH LEVEL TNG. REQD - RADIATION HAZARD - BACKSIDE ACCESS REQD - FILM DEVEL. REQD PLUS VIEWING - THICKNESS/ DENSITY SENSITIVE - FLAW ORIENTATION SENSITIVE	# - BACKSIDE ACCESS REQD - RADIATION HAZARD - LOW RADIATION ABSORPTION MATL OR THIN MATL LIMIT ACCURACY
GENERAL COMMENTS F/S - FACE SHEET U/S - ULTRA SONIC H/C - HONEYCOMB AL - ALUMINUM T - THICKNESS O - REFERENCE (SEE BIBLIOGRAPHY) **NOTE:** ALL TECHNIQUES REQUIRE NDT STDS TO PERMIT QUANTITATIVE USE	APPLICABLE TO METAL LAMINATES AND METAL F/S COMPOSITES ONLY				- BEST METHOD WHEN USED WITH GAMMA RADIO-METRIC - PREDICTS ELASTIC PROP. AND COMPONENT VOL. FRACTIONS	- INCLUSIONS (TEFLON) MOST DIFFICULT TO FIND - DISPLAY TEMPS AS SHADES OF GREY	- BEST RESULTS WHEN COATED, HEATED, VIEWED SIDE IS THIN AND BONDED TO THICKER SIDE (HEAT SINK) NONMETAL LAMINATES ARE BEST	- OPERATIONAL TEST. PERFORATED CORE, OR FIXTURES REQD FOR HIGH STRESS AND LISTEN TO BONDLINE FAILURE NOISE ONLY BONDLINE CONTAMINATION, AFFECTING ADHESIVE BOND STRENGTH, WAS INVESTIGATED	- PICTORIAL DISPLAY GIVES EXCELLENT 3D FLAW RESOLUTION - DISPLAY CAN BE ENHANCED FOR ADDITIONAL INFO - DETERMINE FLAW GEOMETRY BY STEREO, IF REQD	# - PREDICTS ELASTIC PROP. & COMPONENT VOLUME FRACTIONS

Page Intentionally Left Blank

Table 6. NDT Assessment Capabilities - Honeycomb

MEASURES-DETECTS	EDDY SONIC *	ULTRASONIC			X-RAY	THERMAL		ACOUSTIC
		IMPEDANCE	PULSE ECHO	THRU TRANSMISSION		INFRA-RED	LIQUID CRYSTAL	ACOUSTIC EMISSION
LACK OF BOND (F/S TO ADHESIVE)	● ✓ ■ ✓ ▲ NA	● ✓ ■ ✓ ▲ ✓	● ✓ ■ ✓ ▲ ✓	● ✓ ■ ✓ ▲ ✓	● NA ■ NA ▲ NA	● ✓ ■ ✓ ▲ .50 IN D THRU .040 IN T F/S OR LESS (21)	● 1 IN² MIN W/ .190 IN F/S (22) 50 IN D MIN W/.030 - .063 IN F/S (16) ■ .50 IN D MIN W/ .03 IN F/S, 1.00 IN D MIN W/ .063 IN F/S (16) ▲ ✓	● ■ SEE COMMENTS TABLE 5 ▲
LACK OF BOND (ADHESIVE TO CORE)	● ✓ ■ ✓ ▲ NA	● ✓ ■ ✓ ▲ ✓	● ✓ ■ ? ▲ .25 SQUARE (20) (19)	● ✓ ■ ✓ ▲ ✓ (18)	● NA ■ NA ▲ NA	● ✓ ■ ✓ ▲ .50 IN D THRU .040 IN T F/S OR LESS (21)	● SAME AS ABOVE ■ SAME AS ABOVE ▲ ✓	● ■ SEE COMMENTS TABLE 5 ▲
CORE SPLICES	● ✓ ■ ✓ ▲ NA	● ✓ ■ ✓ ▲ ✓	● ✓ ■ ✓ ▲ ✓	● ✓ ■ ✓ ▲ ✓	● ✓ ■ ✓ SEE COMMENTS ▲ ✓ TABLE 5	● ✓ ■ ✓ ▲ ✓	● .020" F/S & BELOW. [PANEL TESTED HAD .020" F/S] (16) ■ .063" F/S & BELOW (16) ▲ ✓	● ■ SEE COMMENTS TABLE 5 ▲
F/S INTERNAL DELAMINATIONS	● NA ■ NA ▲ NA	● NA ■ NA ▲ ✓ (20)	● NA ■ NA ▲ ✓ (19) (20)	● NA ■ NA ▲ ✓ (18)	● NA ■ NA ▲ NA	● NA ■ NA ▲ .50 IN D THRU .040 IN T F/S OR LESS (21)	● NA ■ NA ▲ ✓	● ■ SEE COMMENTS TABLE 5 ▲
BOND STRENGTH (ADHESIVE & COHESIVE)	● NA ■ NA ▲ NA	● COHESIVE ■ COHESIVE ▲ ?	● NA ■ NA ▲ NA	● NA ■ NA ▲ NA	● NA ■ NA ▲ NA	● NA ■ NA ▲ NA	● NA ■ NA ▲ NA	● ADHESIVE - FURTHER WORK REQ EVAL. FOR 3 ADHESIVES ONLY - ONLY METHOD APPLICABLE ■ ADHESIVE ▲ SEE COMMENTS TABLE 5
BONDLINE POROSITY	● + ■ + ▲ NA	+ ■ + ▲ +	● + ■ + ▲ +	● + ■ + ▲ +	● ✓ SEE ■ ✓ COMMENTS TABLE 5 ▲ ✓	● ✓ ■ ✓ ▲ ✓	● ✓ ■ ✓ ▲ ✓	● ■ SEE COMMENTS TABLE 5 ▲
CRUSHED CORE	● + ■ + ▲ NA	● + ■ + ▲ +	● + ■ + ▲ +	● + ■ + ▲ + (18)	● ✓ SEE ■ ✓ COMMENTS TABLE 5 ▲ ✓	● ✓ ■ ✓ ▲ .50 IN D THRU .040 IN T F/S OR LESS (21)	● 3/16 IN D CELL MIN W/.062 IN F/S (22) .25 IN D W/F/S .030 IN, .75 IN D W/F/S .063 IN (16) ■ 1.00" D MIN W/.03-05" F/S (16) ▲ ✓	● ■ SEE COMMENTS TABLE 5 ▲
INCLUSIONS	● ✓ ■ ✓ ▲ NA	● ✓ ■ ✓ ▲ ✓	● ✓ ■ ✓ ▲ ✓	● ✓ ■ ✓ ▲ ✓	● ✓ SEE ■ ✓ COMMENTS TABLE 5 ▲ ✓	● ✓ ■ ✓ ▲ ✓	● 1.25 IN D W/F/S .030 TO .063 IN (16) ■ .50 IN. MIN W/.030 IN - .063 IN F/S (16) ▲ ✓	● ■ SEE COMMENTS TABLE 5 ▲
LACK OF ADHESIVE MATERIAL	● ✓ ■ ✓ ▲ NA	● ✓ ■ ✓ ▲ ✓	● ✓ ■ ✓ ▲ ?	● ✓ ■ ✓ ▲ ✓	● SEE COMMENTS TABLE 5 ■ ▲	● ✓ ■ ✓ ▲ .50 IN D THRU .040 IN T F/S OR LESS (21)	● .5 IN D MIN W/F/S .030 IN TO .063 IN (16) ■ .5 IN D MIN W/.030 F/S, 1.00 IN D MIN W/.063 IN F/S (16) ▲ ✓	● ■ SEE COMMENTS TABLE 5 ▲
TRAPPED MOISTURE	● + ■ + ▲ NA	● ? ■ ? ▲ ?	● ✓ ■ ✓ ▲ ✓	● ✓ ■ ✓ ▲ ✓	● 2cc MIN W/ .020 IN F/S ■ SEE COMMENTS TABLE 5 ▲	● ✓ ■ ✓ ▲ ✓	● .3cc MIN. w/ .020 IN F/S (16) ■ ✓ ▲ ✓	● ■ SEE COMMENTS TABLE 5 ▲

LEGEND:
F/S = FACE SHEET, D = DIAMETER, T = THICKNESS,
HRP = HEAT PHENOLIC RESISTANT
● = METAL F/S (AL) - METAL CORE (AL)
■ = METAL F/S (AL) - NON METAL CORE (HRP)
▲ = NON METAL F/S (F/E) - METAL CORE (AL)
IN = INCHES
W/ = WITH

NA - NOT APPLICABLE
✓ - CAN IDENTIFY, BUT QUANTITATIVE LIMITS NOT ESTABLISHED
? - UNKNOWN

+ - CAN BE DETECTED, BUT DIFFICULT TO IDENTIFY
◯ - REFERENCES (SEE BIBLIOGRAPHY)

* LACK OF ADHESIVE BOND, LACK OF ADHESIVE MATERIAL, AND NON-METAL FACE SHEET DELAMINATIONS PRODUCE APPROXIMATELY THE SAME TYPE OF EQUIPMENT RESPONSE, SINCE ALL ARE BASICALLY LACK OF ADHESION BETWEEN LAYERS OF MATERIALS.

Page Intentionally Left Blank

Table 7. NDT Assessment Capabilities-Laminates (Boron Epoxy and Graphite Epoxy)

MEASURES - DETECT	ULTRASONICS				THERMAL		ACOUSTIC	RADIOGRAPHY	
	IMPEDANCE	PULSE ECHO	THRU XMISSION	VELOCITY	INFRA-RED	LIQUID CRYSTAL	ACOUSTIC EMISSION	X-RAY	GAMMA RADIOMETRIC
DENSITY/POROSITY MODULUS VARIATIONS	✗	✓	✓	±2.5% IN T = .037 IN TO .147 IN ⑭⑮	✓	✓	SEE COMMENT TABLE 5	✗	± 2.5% IN T = .037 IN TO .147 IN ⑭⑮
CURE STATE	?	?	?	✓	?	?	SEE COMMENT TABLE 5	NA	NA
FIBER SPACING & MISALIGNMENT	?	?	?	?	?	?	SEE COMMENT TABLE 5	✓ (IF ENHANCED)	NA
DELAMINATION	✗	✓	✓	.5 IN D IN T = .037 IN TO .147 IN ⑭	✓	✓	SEE COMMENT TABLE 5	SEE COMMENT TABLE 5	NA
OVERLAP	?	?	?	✗	?	?	SEE COMMENT TABLE 5	SEE COMMENT TABLE 5	?
BROKEN FIBERS	?	?	?	?	?	?	SEE COMMENT TABLE 5	✓ (IF ENHANCED)	NA
INCLUSION	✗	✓	✓	✓	✓	✓	SEE COMMENT TABLE 5	SEE COMMENT TABLE 5	✓
FILAMENT/RESIN VOLUME RATIOS	?	?	?	±2% IN T = .037 - .147 IN ⑮	?	?	NA	NA	±2% IN, T = .037 IN TO .147 IN ⑮

LEGEND:

T = THICKNESS
D = DIAMETER

N/A - NOT APPLICABLE
✓ - CAN IDENTIFY, BUT QUANTITATIVE LIMITS NOT ESTABLISHED

✗ - CAN BE DETECTED, BUT DIFFICULT TO IDENTIFY
? - UNKNOWN
O - REFERENCES (SEE BIBLIOGRAPHY)

Page Intentionally Left Blank

variations and discontinuities could be readily met or exceeded. Status of documented quantitative NDT regarding validated NDT data for bonded composite structures is limited. The data obtained is presented in tables 5, 6, and 7. Most of the data on the boron and graphite epoxy laminates presented in table 7 was obtained during the past few years. The tables and associated discussion will be updated as additional data is obtained from in-house studies and published sources.

   c. Assessment Capabilities Discussion for Bonded Composites:

    (1) <u>Summary of NDT Data</u>. Based on the requirements to provide accurate quantitative information regarding discontinuity size, location, geometry, and orientation, the following conclusions may be drawn from an analysis of tables 6 and 7.

     (a) The available data illustrates that the radiographic technique as it is now employed (two percent thickness resolution with beam normal to structure surface) has severe limitations with regard to detection of lack-of-bond conditions (debond, delamination) and low density inclusions. However, the radiographic method is applicable, if structure backside access is available, in providing quantitative information regarding core condition, porosity, splice integrity, and trapped moisture. When applicable in areas shown in table 6, X-ray gives the best flaw resolution in regard to the three-dimensional type of defects in honeycomb structures. For laminates, this method provides quantitative information regarding large porosity, fiber spacing and misalignment, broken fibers, and dense inclusion materials. When applicable, in areas shown in table 7, enhanced X-ray gives the best flaw resolution.

      Beta backscatter NDT radiographic methods may be applicable where access to only one side of the structure is possible, but this will have to be investigated further. Beta backscatter testing methods are limited to thin materials, coatings,or near surface defects.

     (b) For essentially two-dimensional defects, such as lack-of-bond, delaminations, inclusions, and lack of adhesive, thermal methods give excellent quantitative data in regard to location and flaw geometry. Material thickness and density will limit application of this method; however, most bonded structures can be evaluated with either infrared or liquid crystals. The best materials for evaluations with thermal methods are the nonmetal laminates and the metal composites with titanium face-sheets and aluminum core. Equipment and evaluation techniques are relatively simple. Backside access is required for complete evaluation of honeycomb structures.

(c)   In bonded composites, ultrasonic and sonic methods can measure or detect, to some extent (except adhesive bond strength), all discontinuities mentioned in tables 6 and 7; but complexity of scanning equipment, transducer surface contact, and couplants or liquid immersion limit their applications. The through-transmission technique is most definitive for flaw geometry, when backside access is available, but its use is limited to symmetrical structures when a number of items are to be produced. For laminates, ultrasonic velocity is the optimum method to use (when combined with gamma radiometry) to predict elastic properties and component volume fractions. This method is limited to those laminate structures where backside access is available. Information has been received (reference 26) concerning a new ultrasonic method being developed by AVCO for the Air Force Material Laboratories. This is called the "Interval Velocity Technique" which can be used for evaluation of plastic matrix laminate structures from one side only. This technique appears promising for in-place flight hardware evaluations.

(d)   Very little quantitative data are available on the acoustic emission NDT method for measuring adhesive bond strength. It is the only NDT method known, however, which shows any promise of verifying weak bonds which may later result in delamination or lack-of-bond and subsequent structural failure. Stringent process controls on cleanliness and adhesive, limited destructive tests at fasteners or trim-off locations with Portashear and Portapull equipment, and proof pressure or stress tests are the only current methods of checking adhesive bond strength. Note that adhesive bond strength is between adhesive and substrate; cohesive bond strength is the internal bond strength of the adhesive itself. Destructive tests of prototype bonded composite panels or structures should be evaluated dynamically with the acoustic emission method to ascertain (using triangulation methods and three or more transducers) when stressed fiber breaks or debonding occur and where the initial failure starts. This procedure would give useful data feedback to design and fabrication functions.

(e)   For maximum amount of data feedback to design, fabrication, and process control functions, it is concluded that, at the present time:

1.   For bonded honeycomb structure the combination of radiographic, thermal, and ultrasonic methods would be optimum.

2.   For fiber reinforced composites the combination of enhanced X-ray, ultrasonic velocity, and gamma radiometric methods would be optimum.

(2) <u>Structural Analysis Applications.</u> The bonded composite structures described in tables 6 and 7 can be nondestructively analyzed for the range of discontinuities and variations described. Quantitative data for space hardware evaluations is scarce and badly needed at this time. The need for a definitive quantitative approach has but recently been recognized. Previous efforts in applications of NDT analysis to composite structures were primarily directed to solve or determine the extent of a field or production problem in the end item or to develop proprietary data. This yielded much qualitative data and experience, but quantitative data (specific data on NDT equipment range, definition, or confidence level) were limited for finding discontinuities. The effects of variations and flaws in composite structures are still not completely defined from the designer's viewpoint; therefore, design functions seldom specify accept and reject criteria for NDT. When accept and reject criteria are specified, the variations and flaws indicated in tables 6 and 7 are not always mentioned; thus, the quantitative data obtained are limited and scattered.

SECTION IV. STANDARDIZATION CONCEPT

Previous sections indicated that validated quantitative NDT assessment data is not available for many aerospace applications.

This section develops the methodology necessary to provide the reliable quantitative data desired by design and manufacturing elements from the nondestructive testing community. It is necessary to delineate those equipment and flaw definition parameters which must be expressed mathematically to permit the required objective analysis of equipment and techniques.

Paragraph 3. 5. 2. 2 of reference 23 contains recommendations that inspection processes have the capability of detecting all critical defects and that combinations of NDT methods be used for inspecting welds and parent metal. Also, the detection capability of each process used should be known from past experience or should be demonstrated by tests, using production equipment, materials, and process sensitivity.

The various operational aspects of NDT which have been responsible for the lack of uniformity in the collection, analysis, and reduction of data must initially be identified.

Corbly, Packman, and Pearson (reference 24) provided flaw definition parameters for which quantitative values for the NDT data could be established. The definition of a flaw must be provided by the fracture mechanics specialists in order for the flaw definition parameters to become meaningful. The parameters included: (1) sensitivity, (2) accuracy, (3) precision, (4) validity, (5) assurance.

Sensitivity is defined here as the ratio of the number of flaws found by the NDT technique N_f(NDT) to the total number of flaws, N, actually found in the specimen. Thus

$$S(NDT) = \frac{N_f(NDT)}{N} \tag{1}$$

The accuracy of an NDT method in determining true flaw size gives an indication of how close the NDT indication or interpretation of the indication comes to estimating the actual flaw size. If the actual length is $2c_i$, and actual flaw depth a_i, and $2c$(NDT) and $a_{(NDT)}$ are the NDT estimates of the flaw size, the accuracy of flaw size $A_{NDT}(2c)$ and of flaw depth $A_{NDT}(a)$ can be expressed as follows:

$$A_{NDT}(2c) = 1 - \frac{2c_{NDT} - 2c_i}{2c_i} \tag{2}$$

$$A_{NDT}(a) = 1 - \frac{a_{NDT} - a_i}{a_i} \tag{3}$$

For a large number of specimens within a range of actual flaw sizes the accuracy is given by:

$$A_{NDT}(2c) = \frac{1}{N_f} \sum_{i=1}^{i=N_f} \left(1 - \left| \frac{2c_{NDT} - 2c_i}{2c_i} \right| \right) \tag{4}$$

where N_f is the number of flaws detected by the NDT in that particular grouping. The accuracy index varies from zero to unity with the most accurate indication being the higher number.

It is also important to know how often and how well these measurements can be repeated. This quantity is called precision. The basis of an index of precision is the standard deviation of the measurements involved. The standard deviation, sd, is given by:

$$sd = \left\{ \frac{1}{N_f - 1} \sum_{i=1}^{i = N_f} (X_i - \bar{X})^2 \right\}^{1/2} \tag{5}$$

where X_i is the ith measurement

$\bar{X}$ is the mean value of the measurements.

Precision may also be expressed in terms of the probable error defined as:

$$PE = 0.6745 \, sd \tag{6}$$

These terms describe the variability or dispersion of a series of measurements about some mean value. A high degree of precision (low standard deviation or probable error) indicates that measurement of any single indication does not vary greatly from the mean value obtained from a large number of measurements on the same sample.

Validity (or sensitivity to real flaws) is a comparison of flaw definition signals from harmless material discontinuities, such as grain boundaries; these can be erroneously identified as flaws by a given NDT technique if evaluation limits are not clearly established by standards or samples.

A cumulative measurement may be obtained of the sensitivity, accuracies, precisions, validities, etc. , of the NDT method. This combined term will be called an assurance index, $AS_{(NDT)}$:

$$AS_{(NDT)} = S_{(NDT)} A(2c)_{NDT} A(1)_{NDT} A(\theta)_{NDT}$$
$$\cdots P_{NDT}(2c) P_{NDT}(1) \cdots \tag{7}$$

Accuracy and assurance are expressed as dimensionless quantities between 0 and 1, while sensitivity and precision may be expressed as percentages. Thus, the assurance index varies from 0 to 1.

There are basic equipment parameters which are critical to the derivation of quantitative data and the establishment of repeatable practices. These parameters are identified in table 8 for the most common NDT equipment. These basic values, to be specified, must permit the broadest possible application of the equipment for a variety of testing applications, yet control the reliability and system performance. Some aerospace material specifications and military specifications, such as MIL-I-25135 for liquid penetrant inspection materials, already provide this type of information. However, the coverage of NDT equipment and/ or materials is limited to the liquid penetrant and magnetic particle areas with limited coverage of ultrasonic and radiographic materials and equipment. The specific application techniques and equipment settings must be established independently, through correlation by destructive analysis, as described later in this document.

The establishment of guidelines to provide for uniformity in the application of inspection methods is also necessary. Military specifications and American Society for Testing Materials (ASTM) standards are often utilized when applying NDT methods; however, these are usually general in nature and require additional effort to define specific inspection criteria.

The development of uniform equipment calibration standards is also necessary. As a typical example (reference 25):

> In order to accomplish an evaluation of ultrasonic
> instrument performance, the International Institute of
> Welding (IIW) has recommended a test block designed
> to check: (1) instrument amplitude linearity (necessary
> for flaw size estimation), (2) instrument time base
> linearity (for flaw position estimation), (3) resolving
> power, (4) sensitivity, (5) refracted sound path from
> angle beam shoes, and (6) exit point of sound waves
> from the shoe bottom. It has been found, for example,
> that items (5) and (6) are not reliably determined.
> Also, in Europe the resolving power in item (3) refers
> to the ability of the instrument to indicate correctly
> the amplitudes of two signals close together; whereas,
> in America the term is often used to refer to the
> separation of a small signal from a large one.
>
> Therefore, it is becoming essential to have some
> universal means of determining instrument perfor-
> mance and reference calibration so that parts

Table 8. Parameters to be Considered for NDT Equipment Application
(Sheet 1 of 3)

EDDY CURRENT	
NDT Components	Parameters
Probe (Transducer)	Type (Differential, Transformer, Single Coil, etc.) Impedance Size Lift Off Distance Direction
Instrument	Frequency Balance Control Range, Phase, and Amplitude Amplifier Bandwidth Detector, Phase and/or Amplitude Filters, Type (Band pass or Low pass), and Frequency Range Gain Control Alarm, Audio or Visual or Both Signal Polarity Selection Analog Recorder Output Phase and Amplitude Indication Instrument Calibration Standards (conductivity) Material
Specimen	Thickness/Configuration/Accessibility of Specimen Grain Structure and Density Surface Roughness Type and Configuration of Flaws Expected Specimen Flaw Standards
ULTRASONICS	
Probe (Transducer)	Center Frequency Mechanical Q Crystal Material

Table 8. Parameters to be Considered for NDT Equipment Application
(Sheet 2 of 3)

ULTRASONICS (continued)	
NDT Components	Parameters
Probe (cont'd.) (Transducer)	Crystal Size Electrical Impedance at Center Frequency Calibration Curve (Immersion only)

Instrument	Instrument Calibration Standards (Standard ASTM Reference Blocks and IIW Calibration Block, or equivalent)
	Pulse Width ⎫
	Pulse Rate ⎬ Pulser
	Damping ⎪
	Output Voltage Control ⎭
	R. F. and Video Presentation ⎫
	Single and Dual Probe Selector ⎪
	Calibrated Attenuator ⎬ Receiver
	Distance-Amplitude- Correction Gain ⎪
	Frequency Selection ⎭
	Analog Recorder Output ⎫
	Gate and Alarm System ⎪
	Off-On Recorder Output ⎪
	Gate ⎬ Gate & Alarm
	  A - Pulse Width ⎪
	  B - Timing ⎪
	Recording Level ⎭

Specimen	Grain Structure and Density Thickness/Configuration/Accessibility of Specimen Surface Roughness Type and Configuration of Flaws Expected Sensitivity to Couplants Used Specimen Flaw Standards
X-RAY	
Film	Type Speed Size Density Distance (Focal)

Table 8. Parameters to be Considered for NDT Equipment Application
(Sheet 3 of 3)

X-RAY (continued)	
NDT Components	Parameters
Film (cont'd.)	Filters Intensifiers
Instrument	Type (Source) Amperage (ma) Voltage (KV output) Time Instrument Calibration Standards (step wedge, penetrameters)
Specimen	Thickness/Configuration/Accessibility of Specimen Material Density Type and Configuration of Flaws Expected Specimen Flaw Standards

inspected in one facility may be reinspected at another
time in a different laboratory to the same standard.

The development of a device which is currently called
the Electronic Test Block (ETB) was initiated in order
to fulfill a requirement to monitor ultrasonic inspection
systems for the Navy. It was originally intended as a
device, such as "universal test block," to provide the
monitoring inspector with a simple and accurate method
to ascertain that the prescribed test procedures were
being used. As work progressed it became apparent
that several values would accrue from the original
concept.

The following is a partial listing of the capabilities of
the ETB.

1. Monitoring Tool
2. Amplitude Linearity
3. Time Base Linearity
4. Resolution
5. Transducer Evaluation

Since the ETB is capable of simulating flaws and
various material characteristics, it is expected
to serve as a very useful aid in training ultrasonic
operators.

There are, however, certain variations inherent in
any ultrasonic test which must also be considered.
The near and far field effects as well as the
nonpiston-like action of the transducer must be
dealt with in a proper manner. In certain cases,
it just might not be good enough to sense the
sonic amplitude in one portion of the field and
return a simulated echo as if it were a reflection
from another portion of the field. In such instances,
the ETB sensor will have to be placed in the proper
position along the sonic path -- a feat which is not
really difficult but rather cumbersome. Surface
condition is another factor of great importance. In
any ultrasonic inspection, the roughness of the
inspection surface and type of couplant influence the
amount of signal transmitted into and received back
from the part. It is not readily possible to com-
pensate for such variations with conventional test

blocks. However, it should be possible using the
ETB to sense the loss of energy and make a suitable
correction in the electronics.

Probably the most critical requirement for quantitative non-destructive testing, as identified by various researchers, has been that of suitable reference standards. The general consensus has been that artificial flaws produced by jewelers saws, drilling, or even electrical discharge machining are poor substitutes for actual defects. "Natural" defects are difficult to produce, particularly where sizes and orientations are required; and it is difficult to determine their precise dimensional parameters. For example, the detection of the crack-type defects is most critical, hence, the development of crack standards is also critical. It has been demonstrated that a fatigue crack produces a reasonably good simulation; however, it may not be possible to achieve the most desirable orientations due to specimen constraints. In producing any standard, the following requirements must be met:

1. The type, size, geometry, orientation, frequency, and
    location of critical flaws must have been established
    by structural designs.

2. The acceptance/rejection dimensions must be
    bracketed by the simulated defects.

3. The simulated defects must resemble the critical
    defects as closely as possible and have known dimensions.
    The simulated defects should be reproducible and
    inexpensive.

4. Test article parameters such as geometry, surface
    finish, material, and stresses which could influence
    the NDT equipment response should be duplicated or
    simulated in the standard.

5. The sensitivity, accuracy, and precision must be
    verified by correlation with the destructive analysis
    of specimens in which actual defects are intentionally
    produced. The destructive analysis specimen (DAS)
    should simulate all of the standard's parameters which
    could influence the NDT equipment response. The
    DAS should be nondestructively interrogated following
    calibration on the standard. The DAS must then be
    metallographically sectioned and the results statistically
    correlated with the simulated defects in the standard.
    A weld analysis plan (see Appendix) was developed for
    specialized application by MSFC which provides an
    example of an NDT response/destructive analysis

41

correlation. Each particular correlation will have to be tailored to the specific test article/standard requirements. For example, the development of standards for brazed tube joints would be handled differently from welded aluminum plates or fiber reinforced composites. However, the basic considerations of test article/standard simulation and the sequence of testing to establish the adequacy of the standard should not change.

There are NDT methods that provide data where standards with simulated or actual defects are not normally employed, except for unusual situations. Radiography, liquid penetrant, and magnetic particle methods are examples. An NDT/destructive correlation as outlined in the weld analysis plan (see Appendix), and using destructive analysis specimens, would be used to determine the quantitative capabilities of these methods, when required. It should be noted that where NDT standards with simulated or actual defects are not employed, the inspection process uses controls such as radiographic penetrameters, penetrant test emulsification time, etc., which optimize the sensitivity of the NDT method.

SECTION V. RECOMMENDATIONS

A. MANAGEMENT RECOMMENDATIONS

1. GENERAL GUIDELINES

The establishment of basic NDT equipment parameters and the detailed methods of NDT and destructive test correlation should be pursued through program and supporting research channels.

Standard correlation plans will have to be developed for various materials and joining methods. The design constraints and fabrication methods to be utilized in the development of uniformly acceptable equipment calibration and acceptance and rejection standards need to be established. The detailed standard design, fabrication, and correlation must be performed by the using organization in accordance with the established standard guidelines.

A recent NASA solid rocket motor case design criteria monograph, (reference 23), contains the following recommendations which aid in overcoming end item limitations:

42

> If a particular material is to be used under fabrication
> conditions that will produce defects that the inspection
> methods cannot readily detect, and these defects are of
> the critical size or larger, then the case design,
> inspection method, or the fabrication process should be
> modified.

Reference 23, also indicates that the inspection techniques should be changed to methods with increased sensitivity that will readily detect critical-size defects.

Structural designs must not be considered complete and approved until it can be established through destructive and nondestructive testing that the flaws which the designers have determined will cause structure failure can be detected by NDT methods employed to the desired confidence levels.

Quality assurance trained NDT personnel must be permitted by program management to review designs and manufacturing plans to assure inspectability. This can be assured by providing approval blocks for NDT specialists on design and manufacturing plans.

Provisions must be established in program schedules for the development of improved NDT methods in those cases where current NDT technology is not adequate to meet design requirements. New NDT methods or equipment, or both, should only be developed when it has been firmly established that the available systems cannot perform satisfactorily.

Specifications must include acceptance and rejection criteria based upon mechanical properties test data and design allowables, and not upon the limitations of a specific testing technique. As stated in reference 26:

> A limiting factor in applying NDT to predictive testing
> for fracture control is the frequent practice of fabrication
> and hardware specifications describing acceptance and
> rejection criteria in terms of the inherent capabilities of
> common inspection methods. Worse yet, many component
> specifications are undefinitive; for example, "Radiographic
> inspection per MIL-STD-453" and "the weld metal and
> adjacent base metal shall not contain cracks." If fracture
> mechanics and failure experience are to be usefully
> applied, the critical areas and the critical flaw sizes
> required to be nondestructively inspected must be
> established in the technical documentation for a given
> design early in the program.

All factors of the production environment which could influence quantitative NDT must be considered when conducting the NDT and destructive correlation analysis in the development and evaluation of standards and methods. (See Appendix for recommended standard plan.)

A nondestructive inspection manual for maintenance operations developed especially for each major structure, as is now an Air Force policy for future aircraft, must be considered for reusable vehicles such as the Shuttle.

2. TRAINING AND CERTIFICATION OF NONDESTRUCTIVE TEST PERSONNEL

Training must include the preparation of metals, nonmetals, and parts for inspection; applicable procedures and nondestructive inspection equipment and techniques involved, using (but not limited to) magnetic particle, penetrant, ultrasonic, radiographic, eddy current and thermographic inspection methods. Types, causes and characteristics of discontinuities and defects, the effort scope and conditions requiring nondestructive inspection, and the interpretation and evaluation of indications found by various methods of inspection are additional areas which must be covered by adequate training. Instruction should include Specifications and Standards for inspection and regulation governing radioisotopes and applicable safety measures. The training material should be coordinated with the American Society for Nondestructive Testing and training requirements incorporated for qualifying to the SNT-TC-la Recommended Practice Supplements.

Certification of personnel shall include the necessary training (formal or on-the-job) followed by a test examination to ensure the proficiency of each individual. Personnel satisfactorily completing the necessary training and examinations shall be issued a certificate of performance as evidence of certification. The period of effectivity shall be specified on the certificate and inspection personnel shall be recertified at the end of such periods by retesting or other proof of proficiency.

3. PROGRAM INTEGRATION

The NDT planning, development, and implementation activities must be solidly integrated into the hardware development program from the earliest design. This is necessary to achieve a quantitative assessment capability that will be of maximum benefit during the materials screening, manufacturing, development, and qualification testing phases as well as for acceptance testing. The recommended integration of NDT activities into the entire cycle of phased project planning is depicted in figures 1 and 2.

The phase A activities will primarily involve support of the
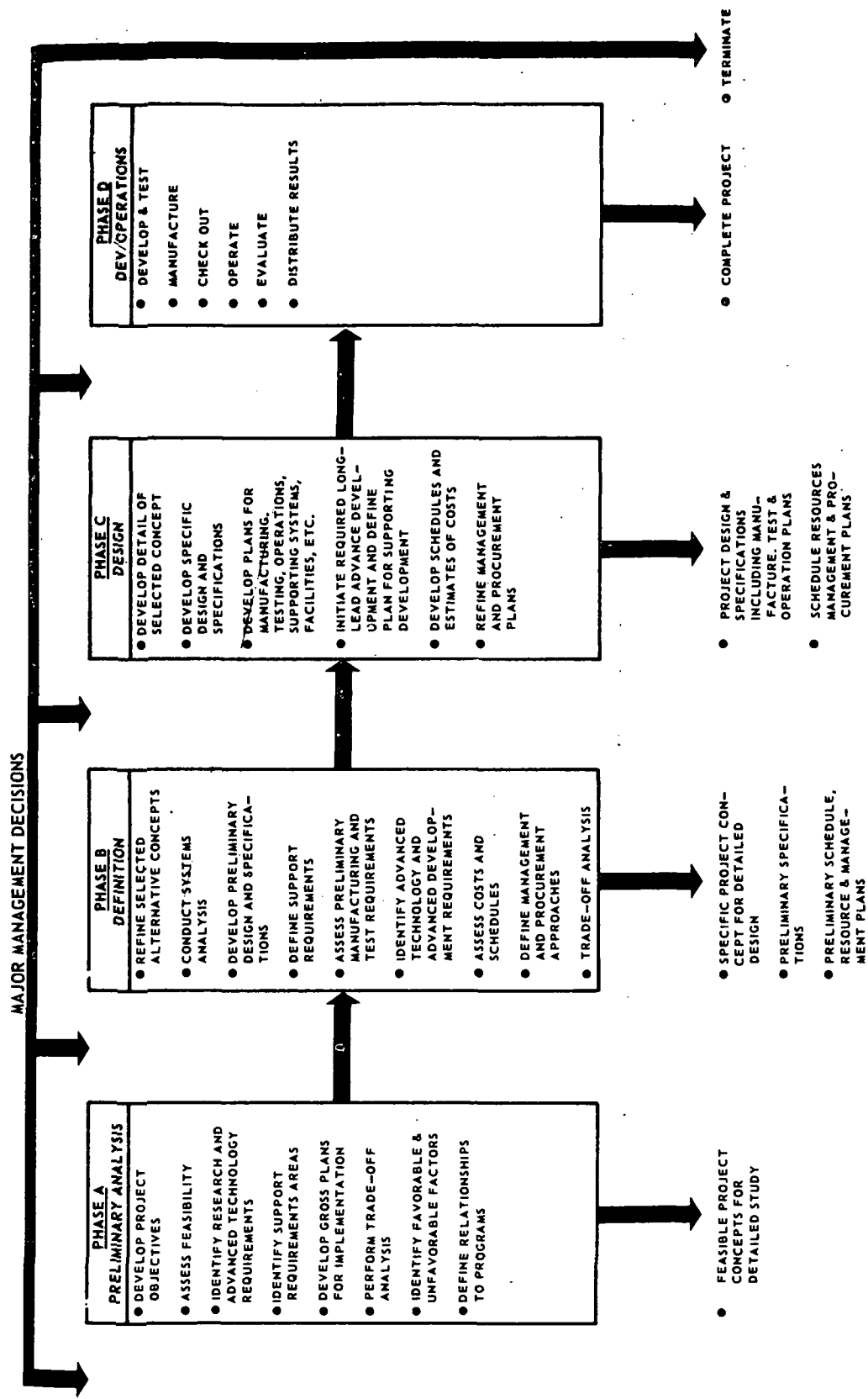
44

Figure 1. Phased Project Planning Phase Relationships
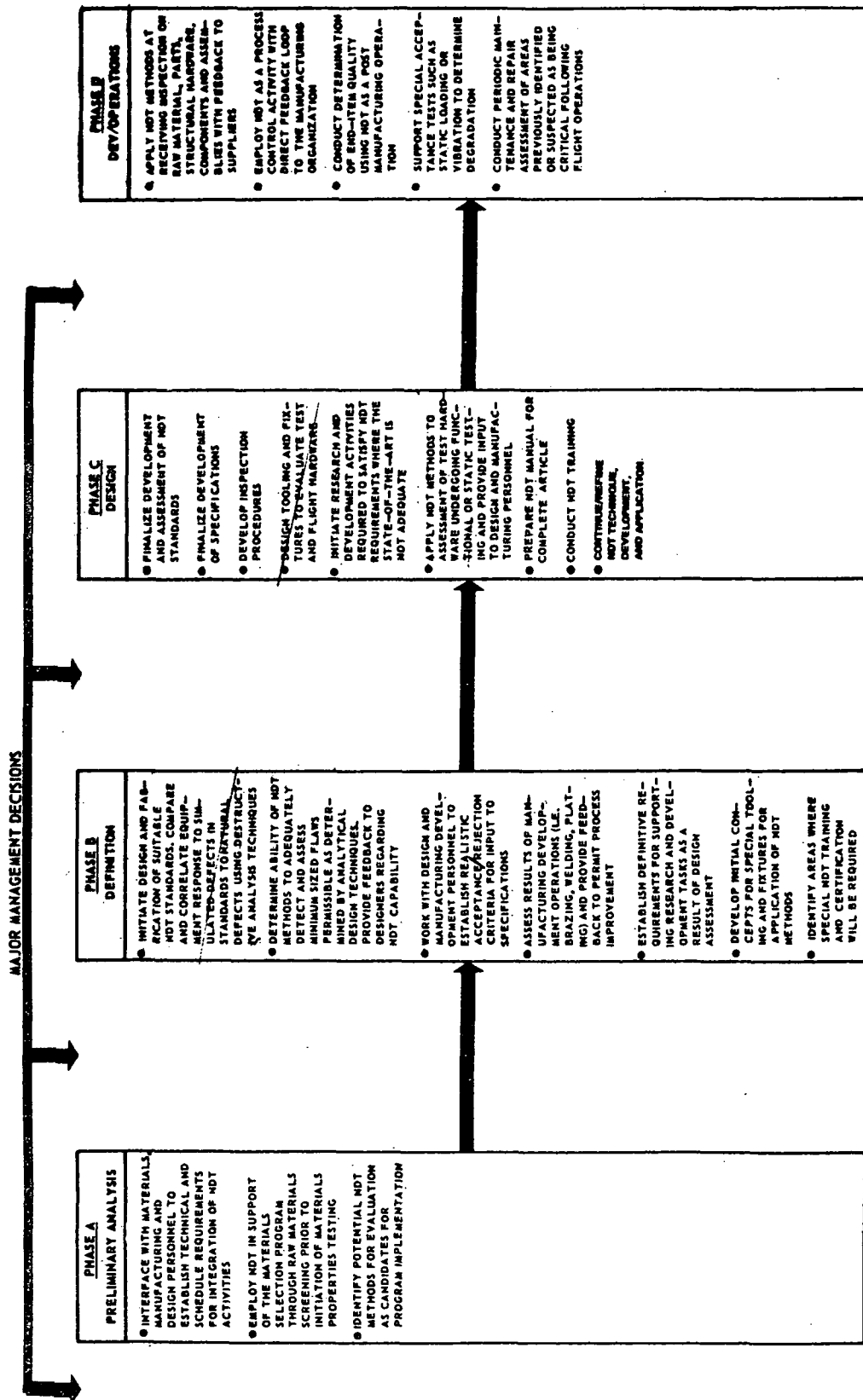
(Reference 29)

Figure 2. Typical NDT Tasks During Project Cycle
(Reference 29)

preliminary screening of candidate materials through correlation of NDT response with physical and mechanical properties data.

The involvement during Phase B will be considerably deeper, requiring the development of acceptance and rejection standards and criteria with feedback to design and manufacturing development elements. The design must also facilitate ready detection by provisions for accessibility for necessary inspections using the available NDT equipment (reference 28). No NDT procedure can be effective if the structure is so designed that "inspectability" is compromised by inaccessibility of the critical areas to the inspection equipment. Thus, the inspectability of the final hardware must be a criterion in the selection of materials and in the assignment of safe operating stresses (reference 2). The areas requiring supporting research and development in NDT will be identified, and preliminary designs for tooling and fixtures will be derived.

The Phase C effort will be aimed at supporting the testing of prototype and qualification test hardware in support of development activities. The development of advanced inspection methods will be conducted where needed; and the specifications, standards, and procedures will be finalized.

The Phase D effort will involve the application of NDT during all phases of the hardware fabrication cycle, from receiving inspection of raw material through end item acceptance inspection and periodic service maintenance.

B.   TECHNICAL RECOMMENDATIONS

There are important areas where research is required in order to develop validated NDT systems for quantitative, useful data. When feasible, the statistical distribution of flaw types and sizes should be determined for the various structural materials and the joining processes used. Priority should be given to those metals which have low fracture toughness, such as metals used for high strength pressure vessels and composites which are most failure prone, or any of those materials where low safety factors will be employed. There are a variety of factors which affect the NDT system response and consequently the capability of NDT methods to resolve material discontinuities. Those components which constitute system "noise" should be identified and their contribution to the total "noise" spectrum established in order to improve system performance. For example, large film grain size contributes to unsharp discontinuity images.

Much work should be done in the analysis of data using computers. The "human element" which is a contributing factor to the unreliability of many methods should thereby be eliminated. The computer enhancement of X-ray film to remove "noise" and sharpen the image is a step in this direction. The data obtained by various NDT methods may also be collected, collated, and analyzed using computers. New NDT methods will have to be developed to fill the gaps created by deficiencies in existing methods, more stringent requirements on materials, and new materials and joining methods. New approaches in data display systems, particularly the holographic type, will be required to display the NDT data from which quantitative information may be derived. Improvements in display technique and equipment may be accomplished through the use of fine grain film for radiography and new "C" scan recording systems.

Research is required to define the capabilities of existing methods utilizing the NDT and destructive analysis correlation methods previously discussed. Improvements in tooling are required which will permit the more rapid and accurate analysis of structures. Existing equipment may be improved through improvements in circuit designs to prevent drift and minimize system "noise."

Where suitable quantitative assessment of structures may prove time consuming, such as high resolution radiography versus conventional radiography, a combination of NDT methods should be considered. For example, a suitably sensitive NDT method, such as ultrasonic, may be used to rapidly scan a weldment for discontinuities and then radiography may be selectively applied to the areas judged defective.

C.   SPECIFIC RECOMMENDATIONS

1.   MATERIALS JOINING

It may be concluded from the assessment of materials joining problems and documentation that the most critical area for research, involving the structural metal alloy systems, requires the derivation of quantitative data regarding weld flaws and establishing the accuracy of such data. More specifically, research should be directed to the analysis of weld cracks and crack type defects for the aluminum, titanium, and high strength steel alloys. The detection of incipient stress corrosion cracking and hydrogen embrittlement are also critical areas for research.

a.   Fusion Welding. Improve the information gathering and processing for both ultrasonic and radiographic techniques by:

48

(1) Developing improved correlation between inspection data, mechanical and physical properties, and service performance.

(2) Electronic scanning of X-ray film and computer processing of the data.*

(3) Automation of ultrasonic testing.

(4) Use of ultrasonic scattering for flaw detection.*

(5) Ultrasonic holography.*

(6) Detection of incomplete penetration in doublesided aluminum welds.*

(7) Correlation of stress-wave emission characteristics with fracture in alloys.

b. Adhesive Bonding. Use new approaches for measurement of both cohesive and adhesive strength.*

c. Mechanical Fasteners.

(1) Develop rapid stress or strain measurement techniques to monitor proper load on fasteners at installation and following service.

(2) Evolve techniques to detect cracks that may be hidden by fasteners.*

d. Brazing. Improve conventional NDT techniques applicable to joints in which a nonmetal is joined to a metal or another nonmetal.*

e. Solid State Diffusion Bonding

(1) Determine debonded areas in diffusion bonded joints.

(2) Develop techniques for measuring compositional gradients by diffusion.*

---

*Reference 30

2. COMPOSITES

Nondestructive evaluation techniques are needed for the detection of flaws and the measurement of key attributes of composite materials. A major need is the increased utilization by industry of techniques presently applied only in the laboratory. A need exists to:

   a. Develop improved correlation between inspection data, mechanical and physical properties, and service performance.

   b. Evolve techniques for the evaluation of fibers and tape prior to composite fabrication.

   c. Study the ability of NDT methods for characterization of new metal-fiber and metal-matrix composites.

3. RESIDUAL STRESS

The magnitude and sign of a residual stress in a part caused by manufacturing or service can be an area of uncertainty in stress analysis. Advanced development is needed to improve existing techniques and to adapt potentially applicable NDT techniques to residual stress problems. A need exists to:

   a. Investigate advanced ultrasonic techniques for the detection of stress.

   b. Make ultrasonic and X-ray diffraction equipment for the measurement of stress more quantitative and more portable for field applications.

   c. Investigate the possibility of using specialized eddy-current techniques to detect residual stress.

4. CORROSION AND STRESS CORROSION

Nondestructive evaluation techniques are needed for the detection and evaluation of corrosion in hidden areas, and a need exists to develop improved correlation between NDT results and the state of corrosion.*

5. FATIGUE

As implied in reference 30, insufficient knowledge is available on either the precursors leading to fatigue or appropriate NDT techniques

to detect the precursors. Improved methods are needed to follow fatigue progression and to predict fatigue life. A need exists to:

a. Develop NDT techniques for identifying precursors of fatigue cracking.

b. Produce equipment for use in-place on complex systems to detect precursors and to monitor progress on fatigue damage.

6. COATINGS*

Improved techniques are needed for measurement or evaluation of thickness, bond, and integrity of a wide variety of metallic and nonmetallic coatings. A need exists to:

a. Develop improved correlation between inspection data and mechanical and physical properties and service performance.

b. Make existing techniques, such as radiation backscatter, thermoelectric, eddy currents, and ultrasonics more quantitative and reproducible. Applicability to various material combinations should be established.

7. ALLOY IDENTIFICATION AND SORTING*

Alloys are frequently specified for critical applications, but despite the ease with which mixing or loss of identification of alloys can occur, little is done to verify alloy composition. A need exists to:

a. Develop equipment combining two or more test methods each with independent response to compositional changes; for example, eddy current and thermoelectric -- now being pursued at MSFC.

b. Develop a lightweight, portable X-ray fluorescent spectrograph and a simple set of calibration standards.

8. DEFECT DETECTION IN ELECTRICAL INTERCONNECTIONS

It is necessary that NDT techniques be developed for detection

---

*Reference 30

of defects and contamination in switches and soldered, plated, and pressure bonded electrical connections. A need exists to:

   a.   Develop an improved NDT technique to detect contamination in electrical switches.

   b.   Develop NDT techniques for soldered electrical interconnectors.

   c.   Develop NDT methods to detect defects in plated-through hole electrical interconnections in multilayer printed circuit boards.

   d.   Develop NDT methods to detect defects in pressure bonded leads to semiconductors.

9.   GRAPHITE AND CERAMICS*

   Many of the NDT techniques normally used for metals are inapplicable on graphite or ceramics. The frequently encountered properties of inhomogeneity, anisotrophy, and brittleness increase the interest in measuring the material attributes as they affect service performance. A need exists to:

   a.   Improve characterization of these materials by nondestructive evaluation as an aid to process control.

   b.   Conduct correlation work to establish the relationship between nondestructive test data and material performance in service.

   c.   Improve existing NDT techniques to provide more sensitive, quantitative results.

10.   SURFACE CLEANLINESS*

   Components frequently have stringent cleanliness requirements to assure proper operation in critical applications, to avoid adverse reaction with the environment, or to assure successful coating, bonding, or other

---

*Reference 30

manufacturing process. Despite these needs, practical quantitative and industrially applicable techniques do not seem to be available. A need exists to:

a. Make investigation into the potential of reflection or scattering for the detection of contamination or embedded particles from processing such as grit blasting.

b. Study low-energy alpha or beta particle attenuation or scatter as a potential tool for cleanliness measurement.

c. Examine high-frequency, ultrasonic waves for possible impedance changes on contaminated areas.

11. THIN MATERIALS*

Instrument limitations have retarded application of NDT techniques in the evaluation of thin materials. Examples of needed development are: higher-frequency eddy-current and ultrasonic instruments, and smaller test probes to achieve greater sensitivity and resolution to small flaws. A need exists to:

a. Make existing techniques more sensitive and quantitative.

b. Develop improved lambda-wave ultrasonic and high-frequency eddy-current equipment for rapid inspection of large surfaces.

---

*Reference 30

REFERENCES

. Tiede, D. A. and Babel, H. W.: National SAMPE Technical Conference, Volume 3, "Detectability of Tight Defects in Aluminum Before, During,and After Load Application," October 1971.

. Report of the NASA AD HOC Committee on Failure of High Strength Structural Materials, August 1971, NASA TMX-68850.

. Packman, P. F., Pearson, H. S., Owens, J. S., and Marchese, G. B., "The Applicability of a Fracture Mechanics - Nondestructive Testing Design Criterion," Report # AFML-TR-68-32, May 1968.

4. The Boeing Company, AFML/TR-67-190 "Large Motor Case Technology Evaluation," August 1967.

5. "Evaluation of NDT Procedure Used for Descent Stage GOX Tanks," Grumman Aircraft Report LRP 52-3, March 4, 1971.

6. Sattler, F. J., "Nondestructive Flaw Definition Techniques for Critical Defect Determination," NASA CR 72602 (Contract NAS8-31121), January 1970.

7. Ostrofsky, B. and Heckler, N. B.: Materials Evaluation, "Ultrasonic Attenuation Measurements for Heat Treat Quality," August 1966,

8. Rummell, W. D.: Materials Evaluation, Characterization and Evaluation of 2014 Aluminum Alloy by Eddy Current Techniques," June 1966.

9. Bland, Jay: Petroleum Refiner, "Ultrasonic Inspection Used to Detect Hydrogen Attack," July 1958.

10. Tryon, R. W.: NASA CR-98355, "Evaluation of the Radiographic Threshold Detection Level of Subsurface Crack-Like Defects in Aluminum Welds," September 1968.

11. Hagemaier, D., Halchak, J., and Basl, G.: Materials Evaluation, "Detection of Titanium Hydride by Neutron Radiography," September 1969.

12. Hannah, K. J., Cross, B. T., and Tooley, T. M.: NASA CR-61952, "Development of the Ultrasonic Delta Technique for Aluminum Welds and Materials," (Automation Industries) May 1968.

REFERENCES (Continued)

13. Hartbower, C. E., "Correlation of Stress Wave Emission Characteristics With Fracture in Aluminum Alloys", Aerojet Solid Propulsion Co., NAS 8-21405 Final Report, November 1971.

14. Zurbrick, J. R.: "Development of NDT for Predicting Elastic Properties and Component Volume Fractions in Reinforced Plastic Composite Materials," February 1969, Report AFML-TR-68-233, U. S. A. F. Contract F33615-67-C-1285.

15. Telecon with J. R. Zurbrick, AVCO, July 24, 1970.

16. Cohen, Sherman E.: "The Application of Liquid Crystals for Thermographic Testing of Bonded Structures," August 1967, Lockheed-Georgia Company, Contract NAS8-20627, NASA CR-88196.

17. Beal, James B., "Ultrasonic Emission Detector Evaluation of the Strength of Bonded Materials," NASA TMX 53602, 1966.

18. Martin, G.: "Nondestructive Testing in the Aerospace Industry," May 1966, Report No. NA-66-465, North American Aviation, Inc., Los Angeles Division.

19. Whealy & Intrieri: "NDT of an Advanced Geometry Composite Blade," March 1969 (Conf. on NDT Plastic/Composite Structures at Dayton, Ohio) The Boeing Company, Vertol Division.

20. Epstein, George: "Nondestructive Test Methods for Reinforced Plastic/Composite Materials," February 1969, AF Report No. SAMSO-TR-69-78, Aerospace Corporation.

21. Telecon with A. Intrieri, Boeing-Vertol, July 23, 1970.

22. Brown, Shelba P.: "Detection of Flaws in Metal Honeycomb Structures by Means of Liquid Crystals," June 1967, Report No. RS-TR-67-5, U. S. Army Missile Command, Redstone Arsenal, Alabama.

23. NASA SP8025, "Solid Rocket Motor Metal Cases," April 1970, NASA Space Vehicle Design Criteria (Chemical Propulsion).

24. Corbly, B. M., Packman, P. F., and Pearson, H. S.: Materials Evaluation, "The Accuracy and Precision of Ultrasonic Shear Wave Flaw Measurements as a Function of Stress on the Flaw," May 1970.

REFERENCES (Continued)

25. Chaskelis, H.H. and Hart, S.D.: "An Electronic Device for Calibrating Ultrasonic Instruments," October 1968, (Presented at the ASNT 28th Annual Conference, Chicago, Illinois).

26. Schultz, A.W., "Development and Application of Nondestructive Methods for Predicting Mechanical Properties of Advanced Reinforced Nonmetallic Composites," June 1, 1970 - April 30, 1971, AF Report No. AFML-TR-71-168, AVCO Government Products Group.

27. "Standard Plan for Evaluation of Nondestructive Testing (NDT) Methods on Welded Structures," Document No. 19/10/4.1, January 1972, NASA/MSFC Quality & Reliability Assurance Laboratory, Analytical Operations Division, Applied Technology Branch (See Appendix).

28. Weiss, H.M.: "Predictive Testing and Fracture Control Technology," July 1971 (Presented at ASTM/NMAB Symposium on Testing for Prediction of Material Performance in Structures and Components, Atlantic City, New Jersey).

29. NASA Handbook NHB 7121.2, "Phased Project Planning Guidelines," August 1968.

30. National Materials Advisory Board, NMAB-252, "Nondestructive Evaluation," June 1969.

APPENDIX

STANDARD PLAN FOR
EVALUATION OF NONDESTRUCTIVE
TESTING (NDT) METHODS ON
WELDED STRUCTURES

PROJECT PLAN
APPLIED TECHNOLOGY BRANCH
ANALYTICAL OPERATIONS DIVISION
QUALITY AND RELIABILITY ASSURANCE LABORATORY

TITLE: STANDARD PLAN FOR EVALUATION OF NONDESTRUCTIVE TESTING (NDT) METHODS ON WELDED STRUCTURES		NUMBER: 19/10/4.1	
BRANCH APPROVAL	DATE	SECTION APPROVAL *JoB*	DATE
COG ENGINEER		TO BE PERFORMED BY	
FUNDING SOURCE		COST ACCOUNT NO.	
DATE ISSUED	DATE REVISED . 11 January 1972	EST START DATE	COMPLETION DATE

CONTENTS OF PLAN

1. HISTORICAL INFORMATION

2. DEFINITION OR DESCRIPTION

3. TECHNICAL SURVEY RESULTS

4. PLANNED APPROACH

5. PROCEDURE & DATA REQUIREMENTS

6. PREDICTED RESULTS

7. IMPLEMENTATION OF RESULTS

8. RESOURCES SUMMARY

NARRATIVE

1. HISTORICAL INFORMATION

    Numerous research tasks and projects have been conducted in the past few years for the purpose of evaluating or determining the capabilities of NDT methods for weld flaw detection. In almost every case, the objective was primarily that of evaluating the capability of a selected method rather than developing NDT methods for detecting and identifying specific defects. Additionally, evaluation of a specific NDT method. usually encompassed evaluating the method's ability for all types of flaw detection. Each task or project was usually conducted independently of previous work and, consequently, data was not readily comparable or relatable from effort to effort.

2. DEFINITION OR DESCRIPTION

    The purpose of this document is to establish a standard plan for evaluation of NDT methods on welded aluminum structures containing commonly occurring internal discontinuities.

    The internal conditions to be considered are:

    a. Porosity - This analysis includes tailed porosity, but excludes micropores less than the average parent metal grain size.

COPIES TO:

SHEET 1 OF ____

R-QUAL-FORM 13 (Feb, 1968) OT

TITLE: STANDARD PLAN FOR EVALUATION OF NONDESTRUCTIVE TESTING (NDT) METHODS ON WELDED STRUCTURES	NUMBER: 19/10/4.1

NARRATIVE (Cont'd)

b. Incomplete Fusion - Lack of fusion and/or penetration.

c. Inclusions - Metallic and non-metallic

d. Cracks - Cracks in any orientation, but above one parent metal grain size in greatest dimensions.

This document does not apply to processing errors, metallurgically damaged (such as over-heated) metal, surface discontinuities, or other flaws not specifically included herein.

For each of the above-listed discontinuities, an optimum NDT method exists. Correlation of programs and data is therefore essential if quantitative comparisons are to be made between methods for detecting flaws; even though radically unlike modes of interrogation are used.

All possible variables shall be removed from the test program. For example, all test panels shall be of a standard alloy, temper, and thickness; with the same weld joint design, and, insofar as practical, the same weld program; (with weld scarfed flush to a 63 RMS finish). The NDT shall be limited, during a single test program, to its applicability to a single class of defect, excluding all others. Data shall be taken only on the class of flaw upon which the NDT is being evaluated. The NDT and subsequent destructive analysis shall follow the procedure for the class of flaw being evaluated. The procedures have been optimized to yield at least 95 percent confidence level in the derived area. The keynote in these programs is to derive R&D plans which assure corollary data for evaluation programs conducted on different NDT methods, at different points and times, by a representative sample of quality control personnel.

3. TECHNICAL SURVEY RESULTS

A formalized program plan does not now exist which will give the assurance of corollary data. Data exists which may be substituted in this total program; however, it is highly subjective in many instances and must be critically evaluated before being included.

4. PLANNED APPROACH

A state of the art survey will be made to provide data for a statistical analysis of capabilities and limitations of existing NDT. This analysis will be made according to the procedures outlined herein. Discrepant areas or deficiencies which reveal a need will be corrected by an R&D program which may be performed inhouse or by contract. In either case, the specific project plan shall include the following data, as applicable:

SHEET 2 OF ____

TITLE: STANDARD PLAN FOR EVALUATION OF NONDESTRUCTIVE	NUMBER:
TESTING (NDT) METHODS ON WELDED STRUCTURES	19/10/4.1

NARRATIVE (Cont'd)

a. Preparation of Test Samples

(1) Internal Cracking* – All 12- by 24-inch test panels shall be composed of two TIG square butt welded 2219-T87 aluminum alloy plates measuring 6 by 24 inches each, in a 0.125-, 0.250-, 0.500-, and 1.00-inch thickness series. A total of 20 cracks in each classification (longitudinal, transverse, or crater) is required for statistical analysis. The number of panels will reflect this requirement, as determined by NDT. Cracking will be promoted by welding without filler and with high heat to produce wide beads.

(a) For longitudinal cracks, the plates at the end where welding is initiated will be tightly fitted, and spread an experimentally determined amount at the finishing end. A second 24-inch pass, at less heat, with filler, may be applied to produce a convex bead. The second side of a double butt weld may be welded by a similar program. Holddown pressure during the weld should be at a minimum.

(b) Transverse cracking may be promoted by a similar weld program, except the joint should be tightly fitted its entire 24-inch length.

(c) Crater cracks may be initiated by starting and stopping the first pass several times within the 24-inch weld length without tapering. The cratered first pass is to be covered with a concealing second pass.

(2) Porosity – All porosity test panels shall be with automatic MIG butt welds extending the 24-inch length of the 2219-T87 aluminum alloy plates. Panels shall be made from plate measuring 6 by 24 inches, in a series consisting of 0.125-, 0.250-, 0.50-, and 1.00-inch thick plate. All thicknesses above 0.250-inch shall be prepared with minimum "Vee" joints. Porosity shall be induced by water vapor contamination of the shielding gas, using a dew point of between -15° and 0°C to induce fine, scattered porosity. Existence of this porosity shall be verified by radiographic examination, with at least 10 well rounded pores visible at close to the 2-2T hole size in the standard penetrameter; very few larger pores shall be visible. Normal logarithmic distribution of pore size will be assumed, to yield a sufficient number of smaller pores for statistical evaluation, so no greater number of panels of each thickness need be welded than meets the above criteria.

* NOTE: Alloys and treatment chosen to have highest probability of production of class of defect. Substitute only where validity of results so obtained is in doubt.

SHEET __3__ OF ____

TITLE: STANDARD PLAN FOR EVALUATION OF NONDESTRUCTIVE   NUMBER:
TESTING (NDT) METHODS ON WELDED STRUCTURES   19/10/4.1

NARRATIVE (Cont'd)

(3) Inclusions (Non-metallic) - All inclusion test panels shall be with manual TIG butt welds extending the 24-inch length of 6061-T6 aluminum alloy plate. Panels shall be made from plate measuring 6 by 24 inches, in a series of 0.125-, 0.250-, 0.50-, and 1.00-inch thick. All thicknesses above 0.250-inch shall be prepared with joints for manual welding. Inclusions (oxide) shall be induced by sulfuric acid anodizing all plates at a voltage of 8-12 volts, producing heavy oxidation in the joint area. The plates shall then be heated a minimum of 16 hours in a dry (electric) oven at 200°C, to eliminate as much absorbed water as feasible. The welds will be made with not larger than 0.115-inch stick electrodes, which have been soaked in water 24 hours and then dried in the oven with the oxidized plate material. Radiographic inspection shall be used to pick up indications of stringer and globular inclusions which will be verified by sectioning at one convenient location, and metallographic determination made of oxide. Radiographic identification of a minimum of 10 stringer inclusions and 10 globular inclusions is required to assure that sufficient borderline occurrences, due to logarithmic distribution of size, will exist for statistical analysis.

(4) Incomplete Fusion - Panels containing lack of penetration and fusion shall be made with the automatic TIG welding method, using square butt welds, extending the full 24-inch length of 2219-T87 aluminum alloy plate.

(a) Panels with lack of fusion shall be made from plates measuring 6 by 24 inches and shall consist of 0.125-inch thickness welded from one side only.

(b) Lack of penetration panels shall consist of 0.250-, 0.500-, and 0.100-inch welded from both sides. The weld schedules shall be selected to produce full fusion for approximately 6-inch initially and to gradually taper in the next 18 inches to a maximum unfused zone at the other, as determined from section cut 2 inches from each end and metallographically examined. A minimum of 20 panels of each type and thickness is required for valid statistical analysis.

b. Test Sample Identification

The test panel identification number shall be stamped permanently into the plate at the upper right corner. On the same side of the panel as the identification, at a distance of 0.25-inch from the edge and 0.5-inch from the center line of the weld bead, a punch mark or number 30 drill mark will be placed, of sufficient depth to show clearly on the radiographs. This will serve as a reference point for all defect location measurements. (See figure 1.)

SHEET __4__ OF ____

TITLE: STANDARD PLAN FOR EVALUATION OF NONDESTRUCTIVE TESTING (NDT) METHODS ON WELDED STRUCTURES	NUMBER: 19/10/4.1

NARRATIVE (Cont'd)

c. **Pretest Inspection**

Prior to acceptance, test panels will be radiographed at 90° and 70°, to determine if the criteria for the type and number of flaws are met. Cracks, lack of fusion and lack of penetration, however, will be determined by sectioning and metallographic examination, with the radiographs as backup evidence of general weld quality. Panels shall be visually inspected at 10X, and all surface defects shall be noted and made part of the data. Panels without desired flaws will be rejected.

d. **Testing (Method Under Test)**

The method under test (MUT), figure 2, will be performed on all test panels accepted through preliminary screening. All tests by a single method and operator on a single flaw type, on all panels, will be completed before starting another series with a different operator. For each MUT, independent tests will be performed using the following table for minimum requirements.

No. Operators	No. Detected Flaws
1	30
2	15
3	10
4	8
5	6

"Detected flaws" as listed in the above table are defined as:

(1) Type of defect being sought, (2) defect not found by X-ray, or (3) defect definition significantly better with the MUT than by radiography. Proper statistical analysis requires that each flaw be reported only once by each operator. If fewer than the required number of reportable flaws are found (per table requirements), additional test panels shall be obtained, qualified, and tested. Defects of the type under test, located and defined by radiography, or means other than MUT, will be similarly reported, so that correlations may be obtained.

e. **Testing (Destructive)**

Each test panel will be subjected to a metallographic analysis upon completion of the MUT evaluation. This evaluation will be based on the defect type being evaluated by the MUT, and will be designed to confirm results obtained on the defect type being evaluated only. Sufficient data will be collected to fully complete the "Test Data" log in figure 3. By defect type, the procedures are as follows:

SHEET 5 OF ____

| TITLE: STANDARD PLAN FOR EVALUATION OF NONDESTRUCTIVE | NUMBER: |
| TESTING (NDT) METHODS ON WELDED STRUCTURES | 19/10/4.1 |

NARRATIVE (Cont'd)

(1) Porosity - Sampling will be used to select pores to be verified by sectioning. A complete listing of "borderline detectable" pores will be established, at the 50 percent detected level (found by 50 percent of the operators using the MUT). If more than 60 pores are listed, the group will be separated into two groups, using individual casts of a single die to keep or discard (odd or even), or coin toss, to obtain a manageable random sample representative of the class. Metallurgical cross sections 0.1-inch thick straddling each sample pore, will be made. The pore will be exposed by successive cuts, 0.001-inch apart. Surfaces will then be polished and etched for visual examination at 10X for verification of identity, size, shape and orientation (where applicable). Any smaller porosity found during the visual examination will be reported and located, carefully estimating the number of pores visible at 10X. The number of pores located on the radiographs by 50 percent of the operators will also be counted, with the points recorded on semi-log paper and a "best fit" curve of area versus number detected, thus constructing a curve to yield an estimate of flaw size versus probability of detection.

(2) Cracks - Cracks have only one important characteristic, which is the projected area under stress. Sectioning will be in a direction and pattern to develop this information fully. The MUT will only be useful if information is obtainable which is not achievable by other methods. Sectioning will be optimized to evaluate cracks and crack extension not detected by conventional NDT. Section will be made in each case at right angles to the average plane of the cracks. The length, width and depth will be determined by ten successive sections cut to give maximum information on crack orientation and dimensions. The projected area shall be recorded as a dimensional sketch with tables giving the desired information. Statistical evaluation will require 30 sectioned cracks.

(3) Incomplete Fusion (Lack of Fusion and Penetration) - Both conditions are linear, consisting of tightly fitted, unfused, vertical joints of remaining base metal and are invariably great in length. Important parameters are average width of zone (projected area per unit length) and extent (end points). The following sectioning procedure is to be followed. A 2-inch long sample cross-section of the weld will be cut straddling the point which has been identified by the MUT as the end of the unfused zone. Each end of this sample will be polished, etched, and visually examined to determine that full fusion was obtained within this section. Upon confirmation, additional sections will be made by cutting away 0.1-inch at a time from either end of the sample until positive identification of the initiation of full fusion is obtained, in that a normal, fully penetrated weld section is obtained.

(4) Inclusions - Oxide (dark) inclusions are the sole type inclusion important to weld quality, (Tungsten inclusions being so infrequent and easily

SHEET 6 OF ____

TITLE: STANDARD PLAN FOR EVALUATION OF NONDESTRUCTIVE TESTING (NDT) METHODS ON WELDED STRUCTURES	NUMBER: 19/10/4.1

NARRATIVE (Cont'd)

located as to be of negligible importance). Oxide inclusions exist in two forms, globular and stringer. Sampling will be used to select inclusions to be verified by sectioning. A complete listing of "borderline detectable" inclusions will be established at the 50 percent detected level, (found by 50 percent of the operators using the MUT). These inclusions are to be divided in classes: Globular, which will be evaluated by the procedure outlined for "porosity", and "stringer" type inclusions, which will be evaluated by the procedure outlined for "cracks".

5. PROCEDURE AND DATA REQUIREMENTS

When using the MUT each defect found by nondestructive testing will be identified starting from the reference point. The test panel number will be first, defect number will be second, and distance from the reference point along the weld centerline will be third. For example, 3-2-0.51 means test panel number 3 and defect number 2, located 0.51 inches from panel reference point. Additional identification, if required to uniquely identify the defect, must be systematic and clearly defined in reporting. Also, at this point each defect (where applicable) will be given size and orientation classification in accordance with figure 2. As each MUT-located defect is correlated to the corresponding destructively located defect, this defect number (corrected where the MUT is in error) will be assigned to the destructively analyzed defect. The nondestructive data will be correlated to the destructive, by use of the defect location information. If, at this point, a minimum of defects for each classification range was not destructively detected, additional test samples will be obtained, as required. For each defect type, an MUT defect summary sheet will be prepared (figure 4). Classification numbers, not actual defect size and orientation, will be entered on this sheet. If the defect was not located nondestructively, the NDT summary blocks will be left blank. If the size or orientation was incorrectly identified nondestructively, the number will be circled. A check (✓) will be entered in the identification block if correct and X if incorrect. Figure 4 is a sample "Test Results Summary" sheet showing eight defects of the type in question as detected by destructive testing, and the nondestructive test results by operator A (test 1) for the same eight defects. These sample test results show that defect 1-5 (the fifth defect occurring in test panel one) was incorrectly sized, correctly oriented, and incorrectly identified; defect 1-4 was incorrectly oriented, and defect 1-25 was not detected.

Upon completion of the test results summarization, the method under test can be statistically analyzed for detectability, sizing, orientation and/or identification capabilities. Any one of these capabilities, but only one at a time, can be selected for analysis. The appropriate data from the "Test Results Summary" sheet is transferred to the "Method Under Test" analysis sheet as shown in the sample data sheet in figure 5. For example, the occurrence of classification 1 porosity, as detected by each of the 30 X-ray tests on 0.125-inch material, is

SHEET 7 OF ____

TITLE: STANDARD PLAN FOR EVALUATION OF NONDESTRUCTIVE TESTING (NDT) METHODS ON WELDED STRUCTURES	NUMBER: 19/10/4.1

NARRATIVE (Cont'd)

simulated in the first occurrence/classification table. The number in each block indicates only the number of defects that were detected for that test in the classification under analysis and does not relate to the accuracy in sizing, orientation, or identification. In analyzing size and/or orientation capabilities, any error in sizing or orientation within a range is disregarded if the defect was placed in the correct classification range. If the defect was placed in the incorrect classification range, it will be considered as an error in sizing or orientation regardless of the degree of error.

After the occurrence/classification table is completed, the arithmetic average (x) and standard deviation (s) are calculated. The standard deviation may be calculated from the following formula:

$$S = \sqrt{\frac{(X_1 - \bar{X})^2}{n - 1}}$$

Where "n" is the number of tests (in this case 30). After the standard deviation and average are computed, the range of defects an operator can be expected to detect out of those actual present with 95 percent confidence level can be computed for the MUT with the following formulas:

$$\text{high limit} - X + 1.96 \frac{S}{n}$$

$$\text{low limit} - X - 1.96 \frac{S}{n}$$

NOTE: Other valid statistical methods may be used if more applicable.

6. PREDICTED RESULTS

Uniformity of evaluation for comparative analysis is the ultimate objective of this plan. By standardizing and reducing the variables involved in evaluating any NDT method, it is possible to obtain corollary data regardless of the time, place, or operator performing the evaluation.

7. IMPLEMENTATION OF RESULTS

In the future, each project involving the evaluation of an NDT method, or developing an NDT method for detecting a specific defect in fusion aluminum welds, shall be conducted in accordance with this plan. The results of these projects, future as well as past, shall be compiled into a perpetual table which will reflect the five basic weld flaws and best NDT method for detecting each type flaw. Additionally, this table will reflect the percent corroboration of that NDT method with

SHEET __8__ OF ____

TITLE: STANDARD PLAN FOR EVALUATION OF NONDESTRUCTIVE TESTING (NDT) METHODS ON WELDED STRUCTURES	NUMBER: 19/10/4.1

NARRATIVE (Cont'd)

actual flaws as determined by destructive test. This table shall be made available on a continuing basis to all cognizant groups at MSFC.

SHEET 9 OF ____

R-QUAL FORM 13-1 (Feb, 1968) OT
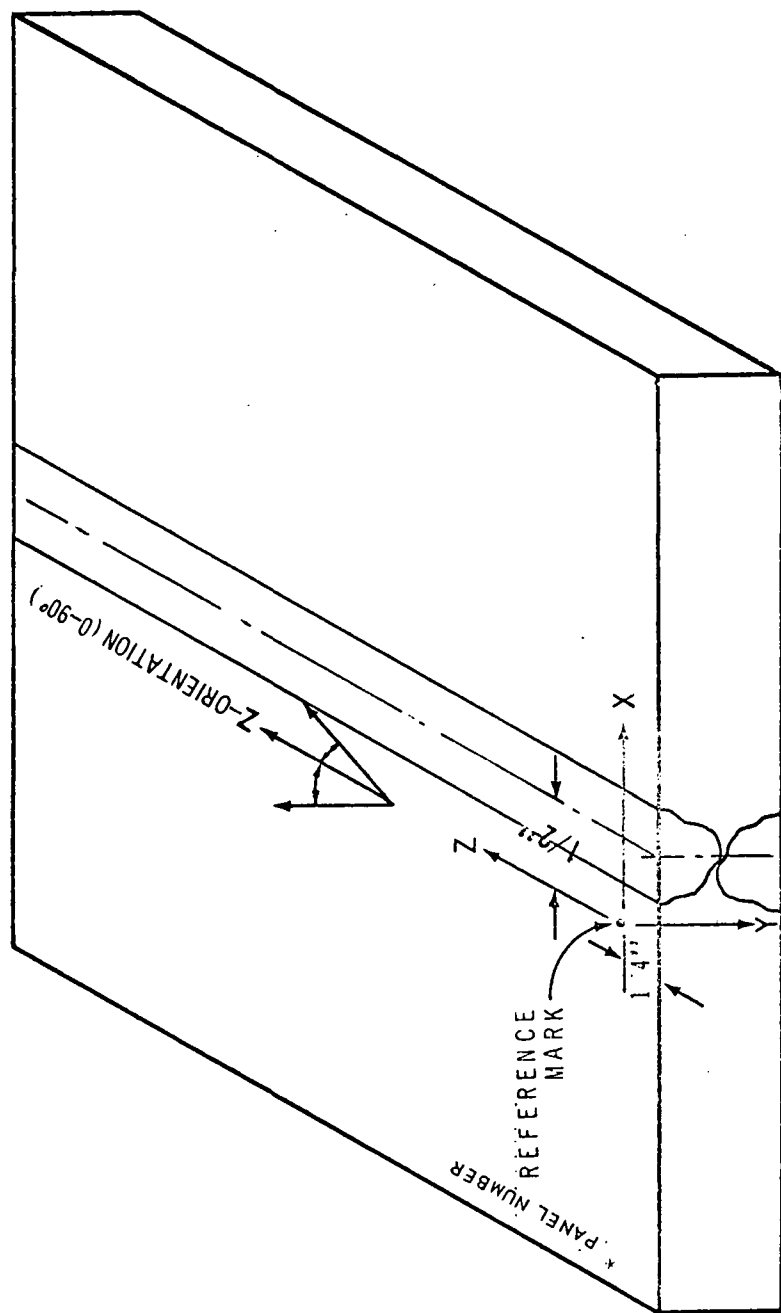
LENGTH – Z DIRECTION
HEIGHT – Y DIRECTION
WIDTH – X DIRECTION

Z-ORIENTATION (0–90°)

X

Z

1/2"

REFERENCE MARK

1 4"

PANEL NUMBER

Y

Y-ORIENTATION (0–90°).

FIGURE I

FIGURE 2

A-12

TEST DATA

TEST METHOD _____

PANEL No. _____

OPERATOR _____

DATE _____

● REFER TO FIGURE 3

DEFECT TYPE	DIMENSIONS			ORIENTATION ●		LOCATION ●			THIS INFORMATION TO BE COMPLETED AFTER TESTING			
	WIDTH	HEIGHT	LENGTH	Y	Z	Y	Z	X	DEFECT No.	CLASSIFICATION RANGE		IDENTIFICATION
										SIZE	ORIENTATION	

FIGURE 3

A-13

TEST RESULTS SUMMARY
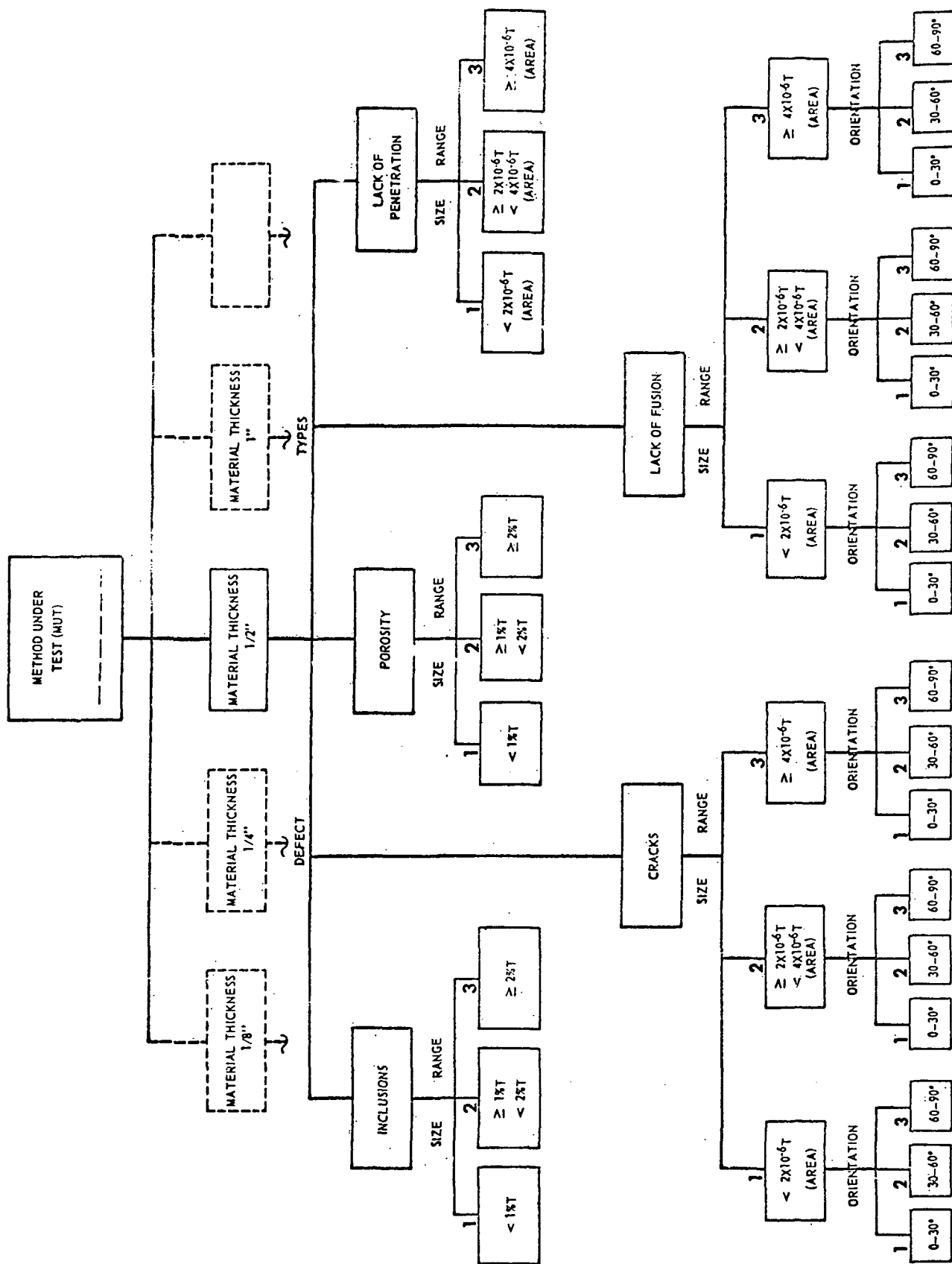
METHOD UNDER TEST

DEFECT TYPE

NDT SUMMARY

TEST	1			2			3			4	5		7	8	9	10
OPERATOR	A			A			A			A	A		C	C	C	C
	SIZE	ORIENTATION	IDENTIFICATION	SIZE	ORIENTATION	IDENTIFICATION	SIZE	ORIENTATION	IDENTIFICATION							
	2	1	*													
	2	1	*													
	2	⊖	*													
	⊖	1	X													
	1	2	*													
	3	1	*													
	1	2	*													

DESTRUCTIVE TEST SUMMARY

PANEL No.	DEFECT	CLASSIFICATION	
		SIZE	ORIENTATION
1	2	2	1
1	3	2	1
1	4	2	3
1	5	1	2
1	8	1	1
1	12	3	2
1	25	2	2
1	26	1	2

LEGEND – NDT RESULTS SUMMARY

1,2 OR 3 – CORRECT ORIENTATION OR SIZE
* – CORRECT IDENTIFICATION
BLANK – NOT DETECTED

①②OR③ – INCORRECT ORIENTATION OR SIZE
X – INCORRECT IDENTIFICATION

FIGURE 4

MSFC – Form 3376-1 (April 1966)

A-14

METHOD UNDER TEST ___X-RAY___
DEFECT TYPE ___POROSITY___
MATERIAL THICKNESS ___1/8"___
CONDITION UNDER ANALYSIS ___DETECTABILITY *___

OCCURRENCE / CLASSIFICATION ___1-1___ (<1%T, 0-30°)

OPERATOR	TEST NUMBERS									
	1	2	3	4	5	6	7	8	9	10
A	6	6	5	7	4	6	6	6	5	6
B	5	4	4	7	4	6	4	5	4	4
C	7	7	7	7	6	7	7	7	6	7
D										
E										

ACTUAL DEFECT COUNT 10
s 1.7
X̄ 5.8
5.2 TO 6.4 OUT OF 10 DEFECTS CAN BE DETECTED WITH A 95% CONFIDENCE LEVEL

OCCURRENCE / CLASSIFICATION ___2-1___ (≥1%T, <2%T, 0-30°)

OPERATOR	TEST NUMBERS									
	1	2	3	4	5	6	7	8	9	10
A										
B										
C										
D										
E										

OCCURRENCE / CLASSIFICATION ___3-1___ (≤2%T, 0-30°)

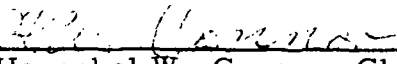| OPERATOR	TEST NUMBERS									
	1	2	3	4	5	6	7	8	9	10
A										
B										
C										
D										
E										

FIGURE 5

* OR SIZING, ORIENTATION, OR IDENTIFICATION

APPROVAL

ASSESSMENT OF AND STANDARDIZATION FOR QUANTITATIVE NONDESTRUCTIVE TESTING

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.
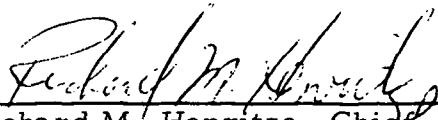
This document has also been reviewed and approved for technical accuracy.

Herschel W. Connor, Chief
Materials Analysis Section

John M. Knadler, III, Acting Chief
Applied Technology Branch

Richard M. Henritze, Chief
Analytical Operations Division

Dieter Grau, Director
Quality and Reliability Assurance Laboratory

DISTRIBUTION

DIR/Dr. Rees
S&E-QUAL-DIR/Mr. Grau
S&E-QUAL-A/Mr. Henritze
S&E-QUAL-AA/Mr. Walker
S&E-QUAL-AFR/Mr. Reynolds
S&E-QUAL-AAS/Messrs. Dickson/Goodwin
S&E-QUAL-AR/Mr. Knadler
S&E-QUAL-ARA/Mr. Beal (50)
S&E-QUAL-E/Mr. Davis
S&E-QUAL-OCP/Mr. Krone (3)
S&E-QUAL-AE/Mr. Donaldson
S&E-QUAL-EF/Mr. Logan

SS-H-X/Mr. Neuschaefer (2)

PD-DIR/Dr. Mrazek
S&E-SP-EM/Dr. Thomason
S&E-ASTN-DIR/Mr. Kingsbury
S&E-ASTN-ME/Dr. Gause/Mr. Clotfelter
S&E-ASTN-M/Mr. Schwinghamer
S&E-ASTN-ES/Mr. Engler
S&E-ASTN-E/Mr. Kroll
S&E-PE-MX/Messrs. Brown/Walker
S&E-PE-D/Mr. Weckwarth
S&E-PE-MW/Mr. Parks

MSC:
NA/Mr. M.L. Raines
    Mr. L. Menear
    Mr. R. E. Johnson
    Mr. J. Cohen

KSC:
QA/Mr. R. A. McDaris
    Mr. S. Beddingfield
    Mr. R. A. Sannicandro

GSFC:
310.0/Mr. R. Dorrell

ARC:
PER/Mr. F. DeMuth

LaRC:
  115/Mr. E. Britt
      Mr. R. Anderson
      Mr. W. A. Brooks, Jr.

LeRC:
  1020/Mr. S. Perrone
      Mr. R. L. Davies (2)

NASA Headquarters:
KR/Mr. H. M. Weiss (10)
MHQ/Mr. G. Eriksen
MQ/Messrs. H. Cohen/G. White
RS/Mr. A. O. Tischler
RW/Mr. G. Deutsch

Commanding Officer, U.S. Army
Materials Research Agency
ATTN: AMXMR-TMT,
      Nondestructive Testing
      Information Analysis Center
      Watertown, Mass. 02172

A& PS-PAT
A& PS-MS-IP (2)
A& PS-MS-IL (8)
A& PS-MS-H
A& PS-TU (6)

Scientific and Technical
  Information Facility (25)
P.O. Box 33
College Park, Md. 20740